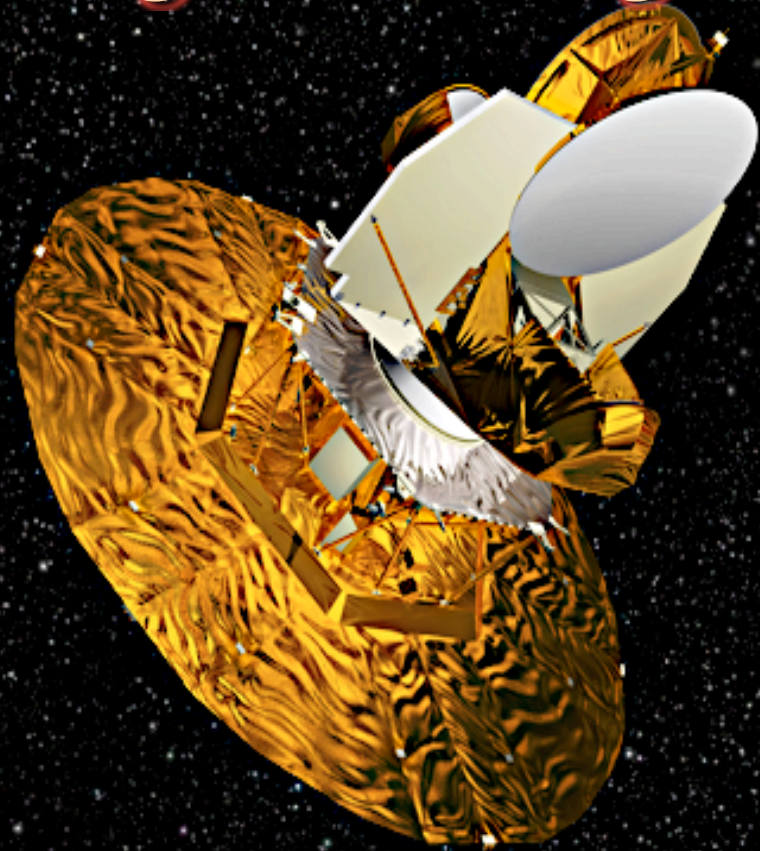


WMAP 3 years of observations: Methods and cosmological insights



Olivier Doré

*CITA / Princeton University
on behalf of the WMAP science team*

WMAP Science Team

NASA - GSFC GODDARD

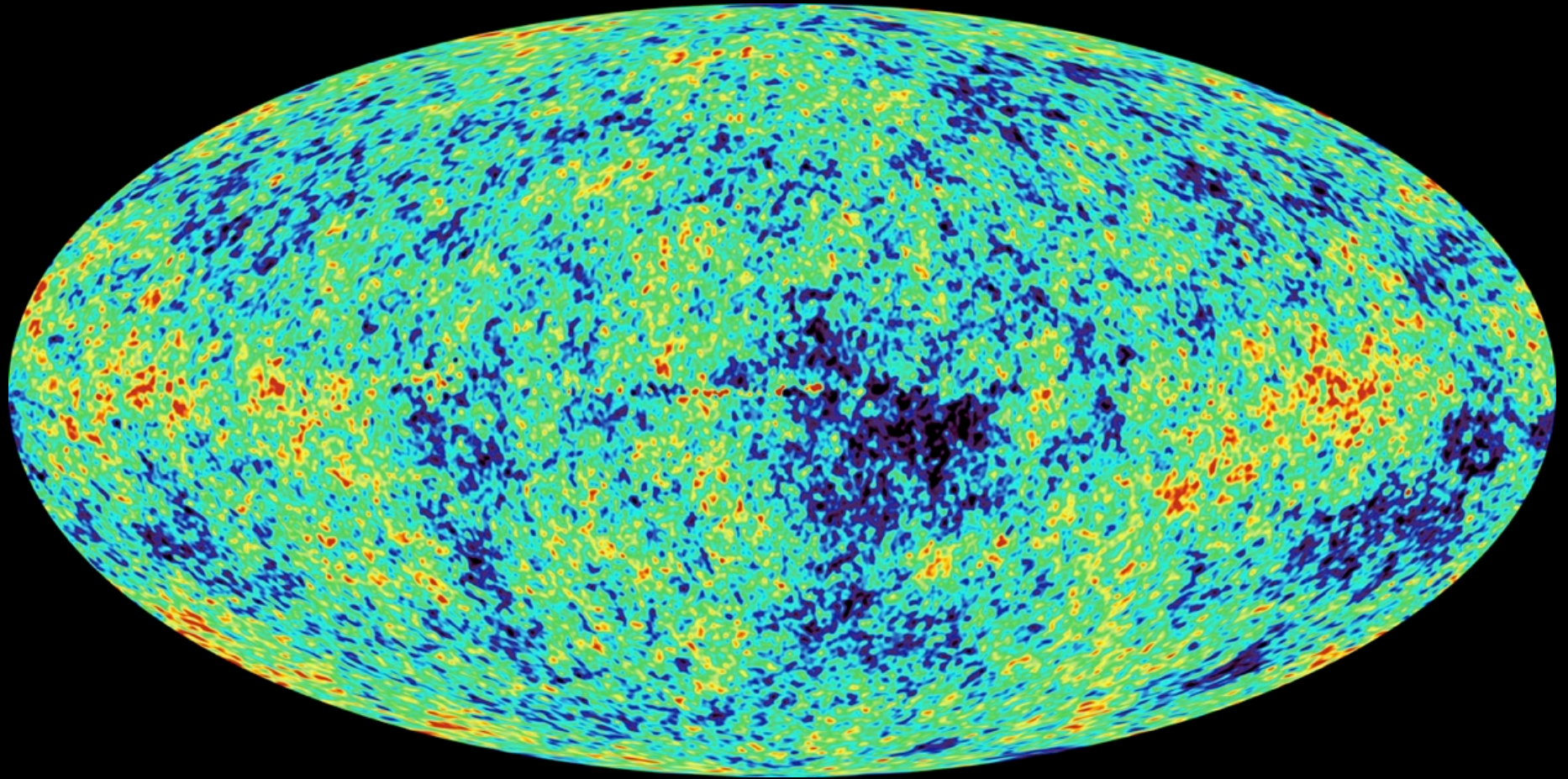
C. Bennett (JHU)
G. Hinshaw
R. Hill
A. Kogut
M. Limon
N. Odegard
J. Weiland
E. Wollack

PRINCETON

C. Barnes
R. Bean (Cornell)
O. Doré (CITA)
M. Nolta (CITA)
N. Jarosik
E. Komatsu (Texas)
L. Page
H. Peiris (Chicago)
D. Spergel
L. Verde (Penn)

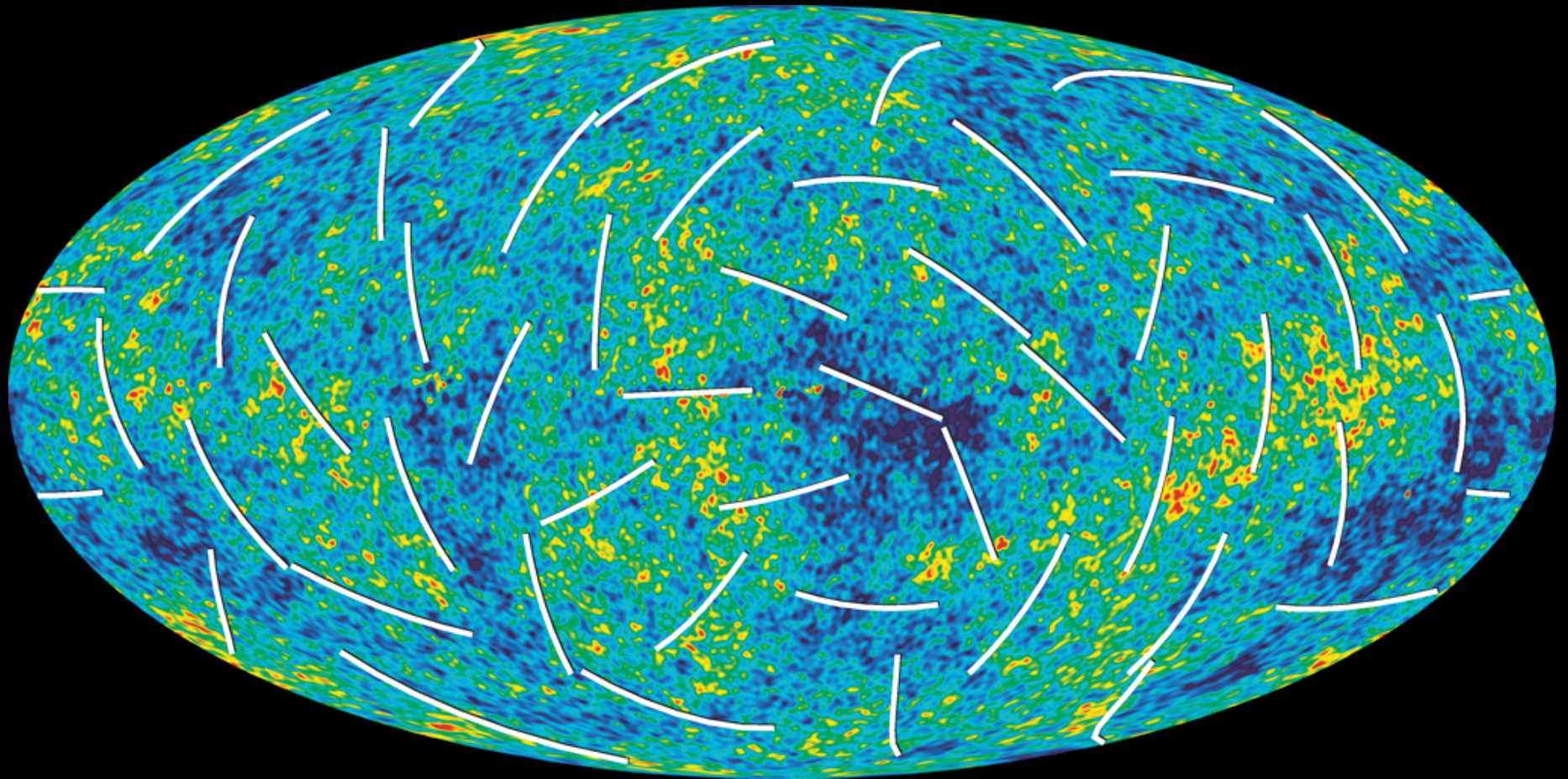
M. Halpern (UBC)
S. Meyer (Chicago)
G. Tucker (Brown)
E. Wright (UCLA)

What has WMAP-1 done for us ?



- Color codes temperature (intensity), here $\pm 100\mu\text{K}$
- Temperature traces gravitational potential at the time of recombination, when the Universe was $372\,000 \pm 14\,000$ years old
- The statistical analysis of this map entails detailed cosmological information
- WMAP-1 has improved over COBE by a factor of 45 in sensitivity and 33 in angular resolution
- The mission met all its requirements after the first year... "Mission Accomplished!"... but...

What has WMAP-3 done for us?



- ... but the insights expected on **Inflation theory** ($\sim 10^{-18}$ s after BB) and the **Universe reionization** (364^{+124}_{-74} Myr) from large scale CMB polarization measurements were to tempting to not be pursued
- WMAP-3 has now improved over COBE by a factor of 77 in sensitivity and 33 in angular resolution
- WMAP-3 has measured the CMB polarization on very large angular scales
- To do so required us to improve control the systematics at a level 50 times higher than originally proposed!

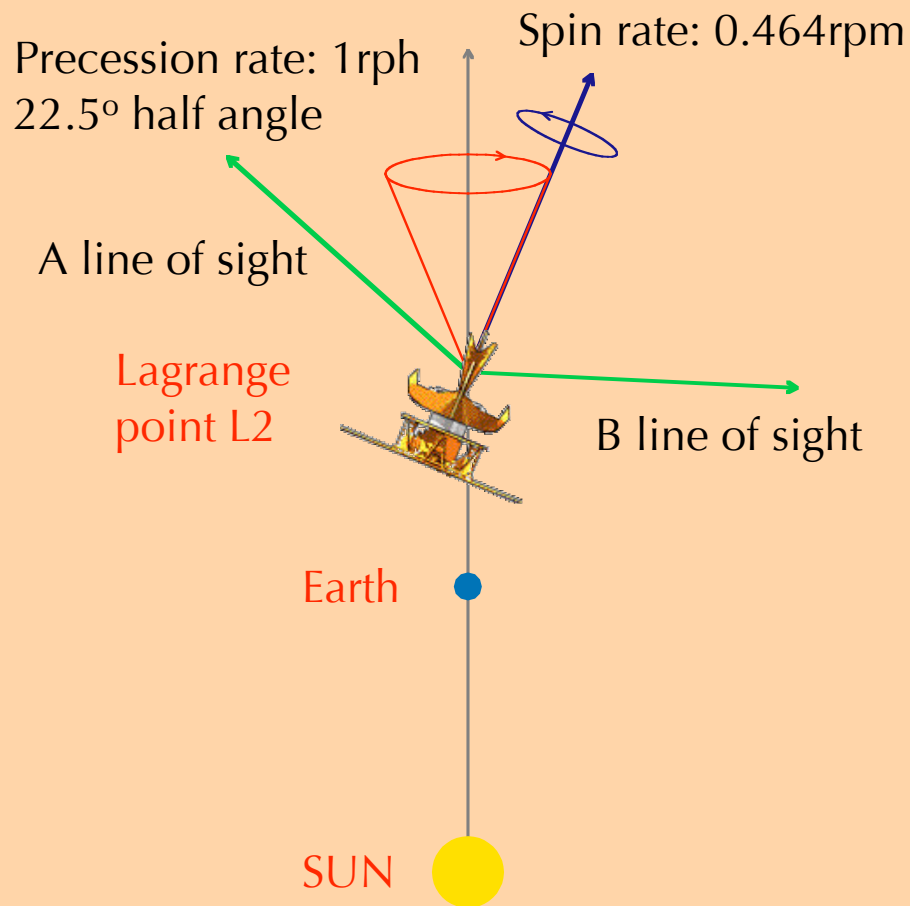
Outline

- Recap on WMAP and analysis improvements over the last 2 years
- A case for large scale polarized CMB detection
- Cosmological implications
 - *Phenomenological success of Λ CDM cosmology*
 - *WMAP already addresses new set of questions risen by this success*

I can't cover it all now. Please ask questions.



WMAP primer



- L2 orbit
 - Constant survey mode
 - Thermal stability
 - Passive cooling
- Rapid and complex sky scan
 - Observe 30% of the sky every day
 - Most of pixels are observed with evenly distributed orientations
- Differential measurement only
 - Most of the common modes cancel
 - Two radiometers per feed
 - $T_1 + T_2 \propto \text{Intensity}$
 - $T_1 - T_2 \propto \text{Polarization}$
 - 10 feeds, 20 DA total
- 5 microwave frequencies to monitor foregrounds
 - K, Ka, Q, V, W bands
 - 22, 33, 40, 60, 93 GHz
- Accurate calibration on the cosmological dipole and beam measurements on Jupiter

Remarks on the analysis over the last 2 years

- Differential measurement and interlocked scanning strategy suppresses polarization systematics as for temperature.
- No new systematics, but the weak nature of the spinorial polarized signal requires extra-care to avoid any coupling to the much stronger T field (100 times).
- Non-trivial interactions between the slow drift gain, non-uniform weighting across the sky, time series masking, $1/f$ noise, galactic foregrounds, band-pass mismatch, off-set sensitivity and loss imbalance.
- The handling of these effect had to be propagated from the map-making till the power-spectrum measurement.
- To understand them required numerous end-to-end simulations (enough to have good statistics). Most of 2004-5 was spent running those and realizing that the previous short-cuts did not work anymore.
- A new pipeline was eventually required and has been designed, written and optimized.
- We rely heavily on null tests in map (various frequency) and C_l space to assess the quality of this processing

Temperature maps

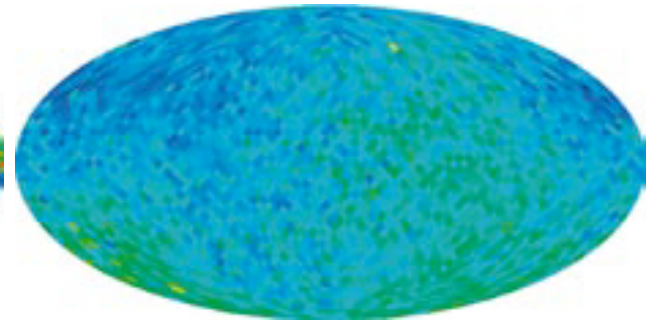
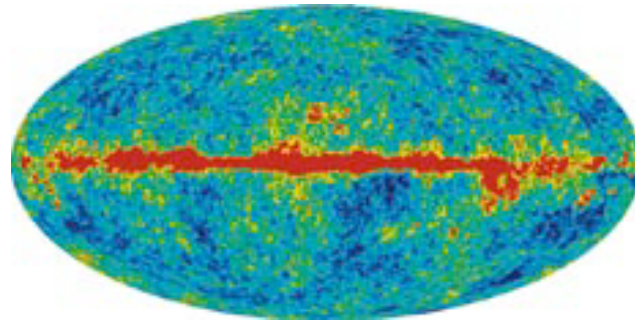
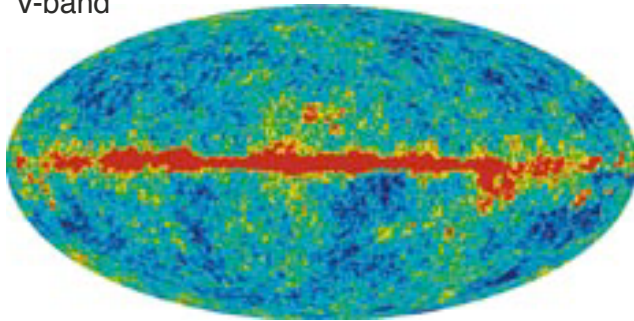
V band

year 1 (pub)

year 3

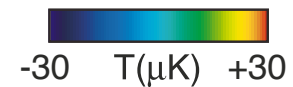
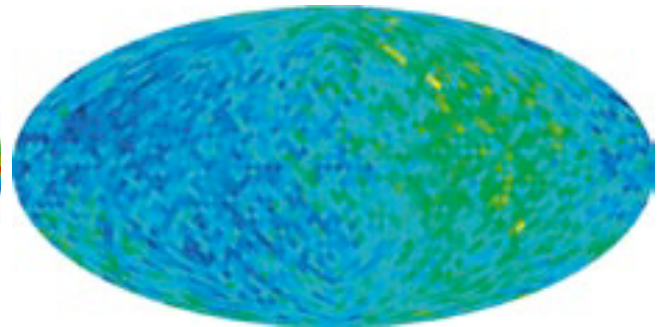
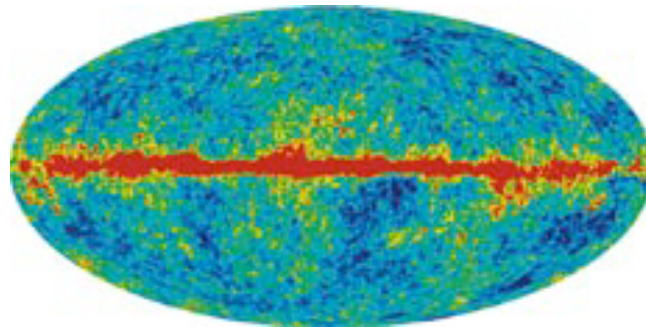
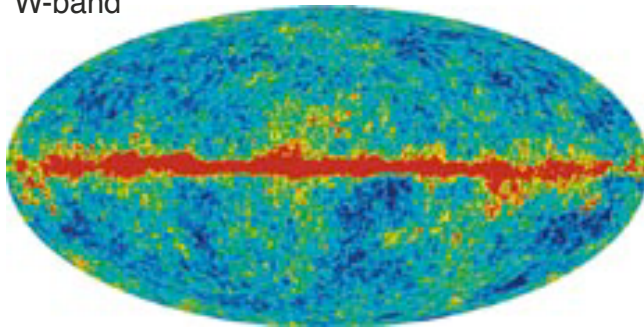
year 3 - year 1

V-band

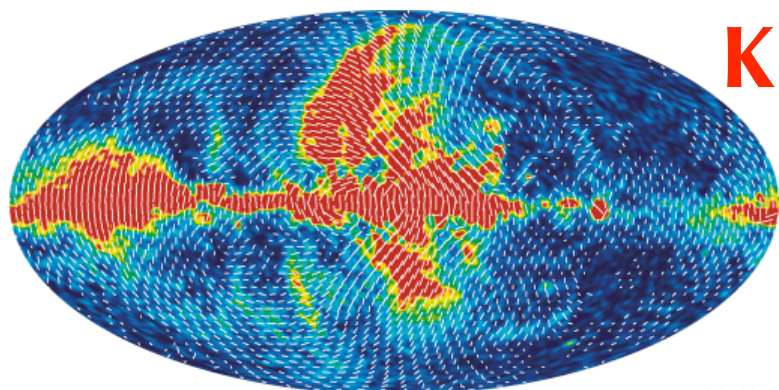


W band

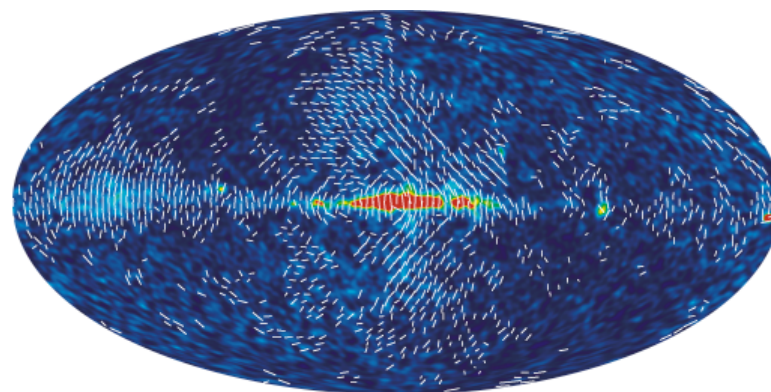
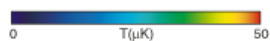
W-band



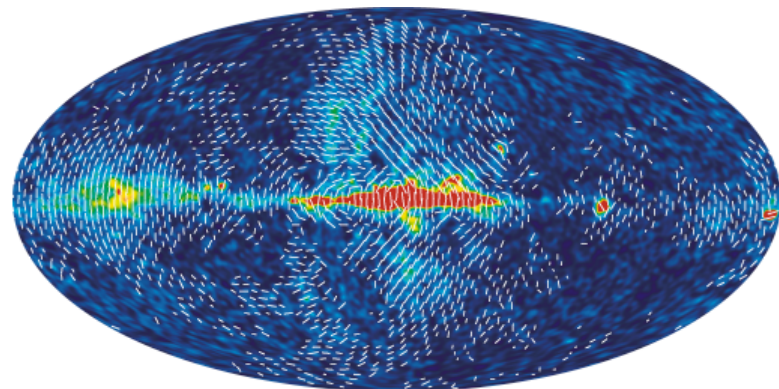
Polarization maps



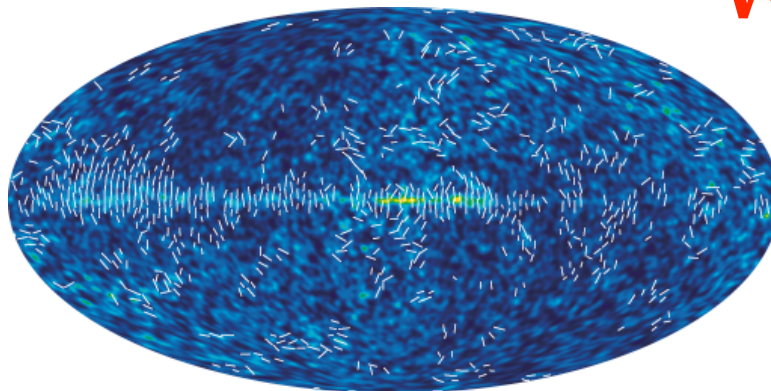
K band



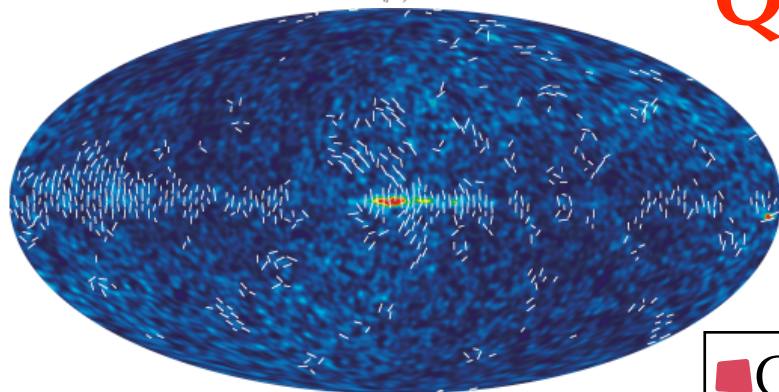
V band



Ka band



W band

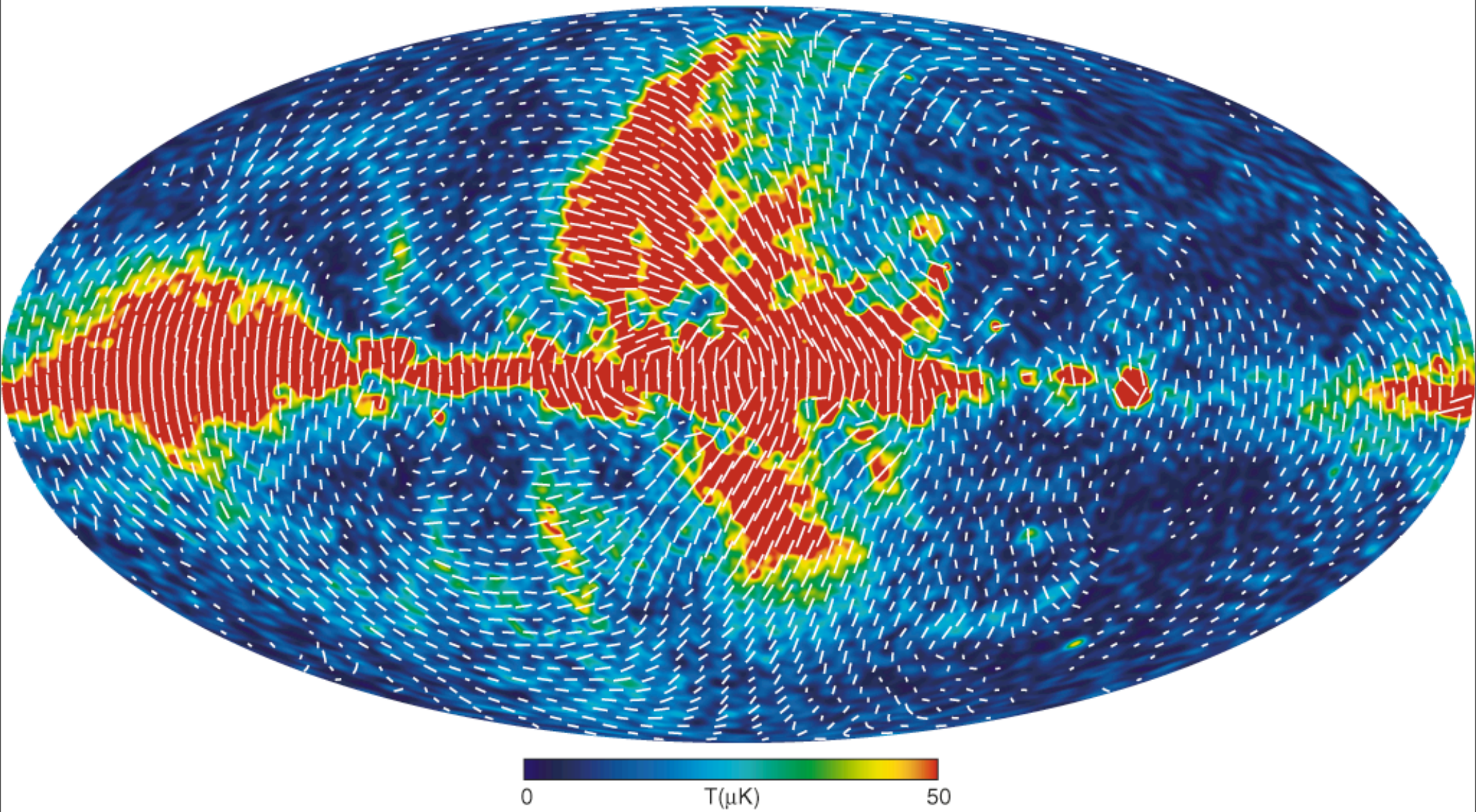


Q band

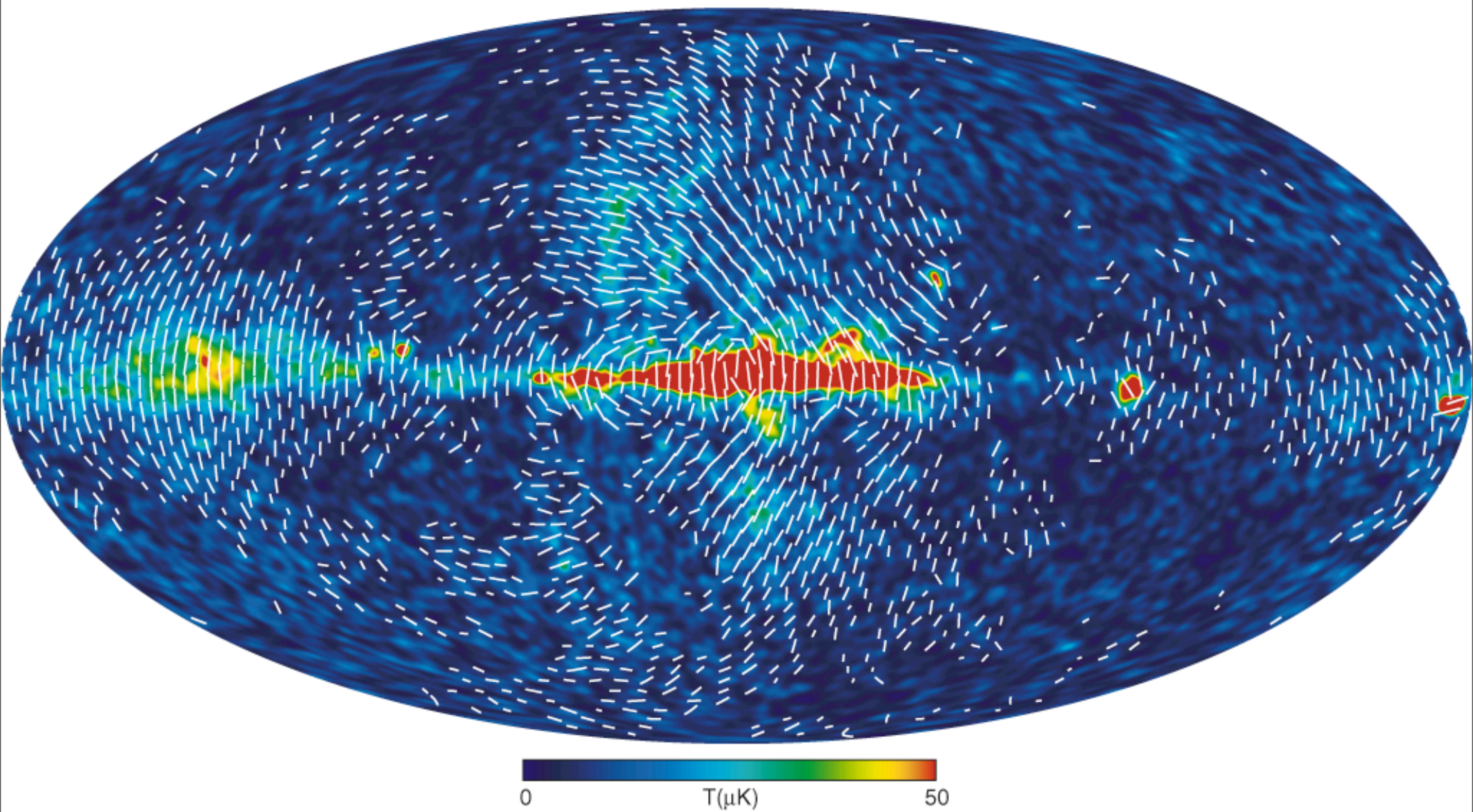


■ Color code $P=(Q^2+U^2)^{1/2}$ smoothed with a 2° fwhm
■ Direction shown for $S/N > 1$

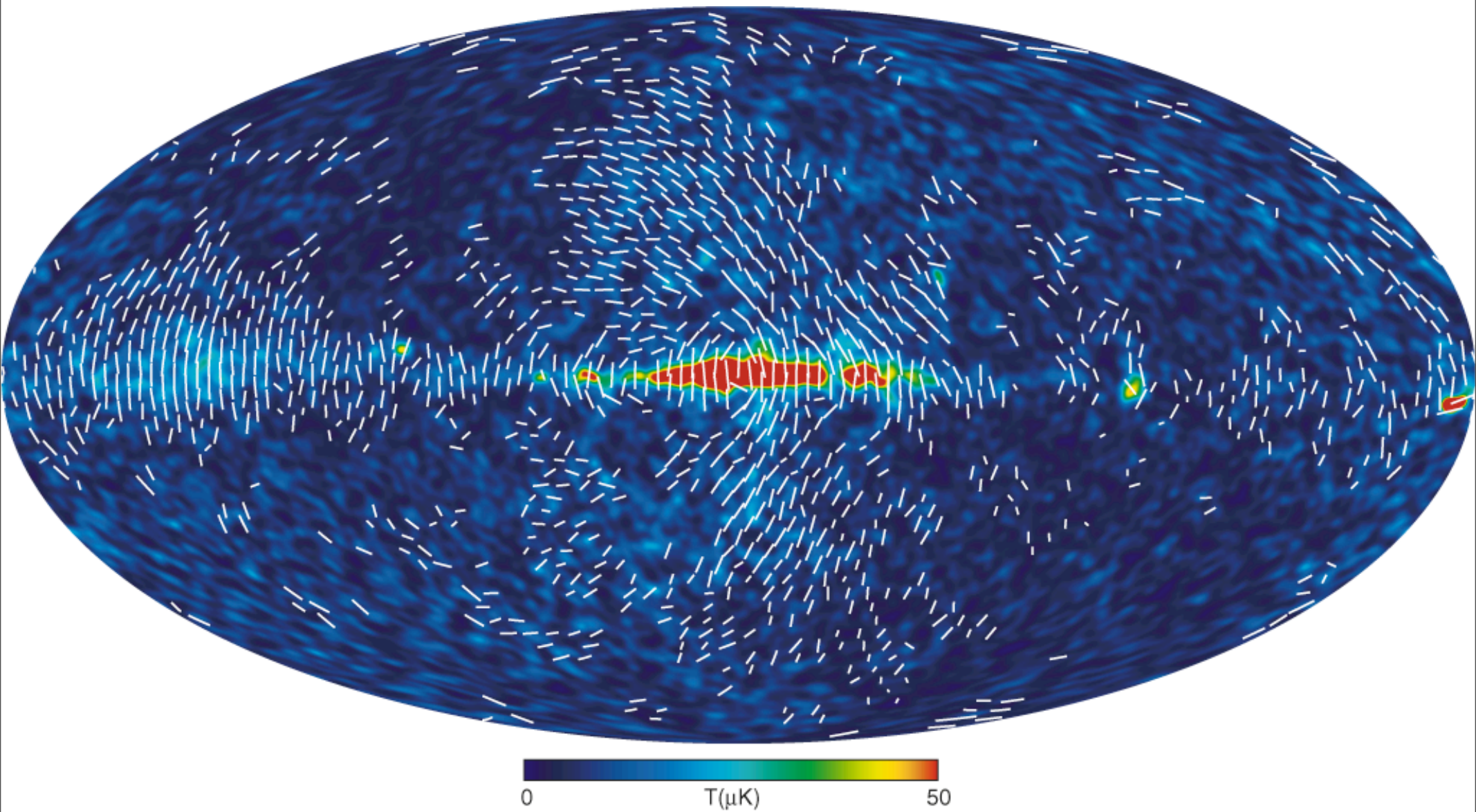
K band - 23 GHz



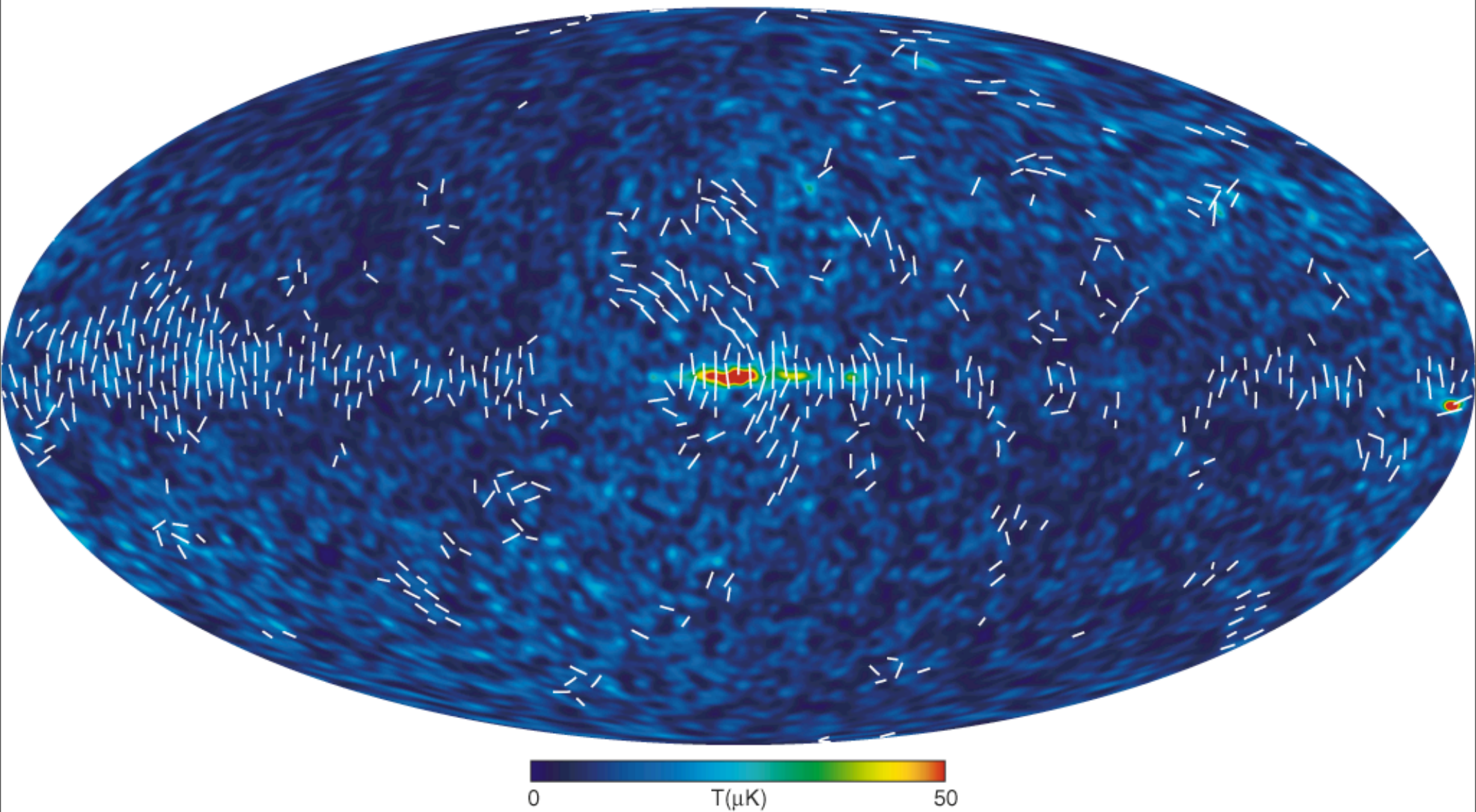
Ka band - 33 GHz



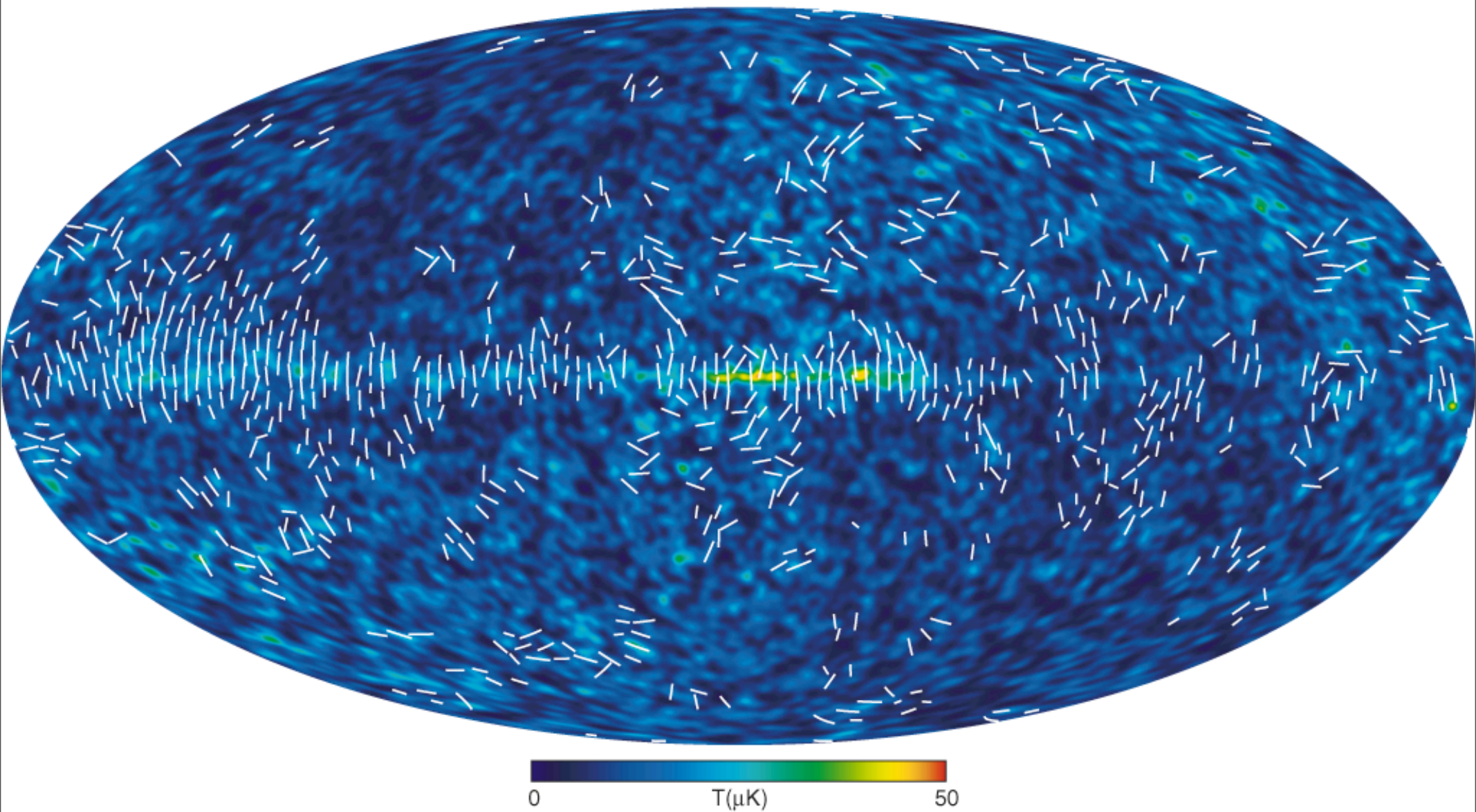
Q band - 41 GHz



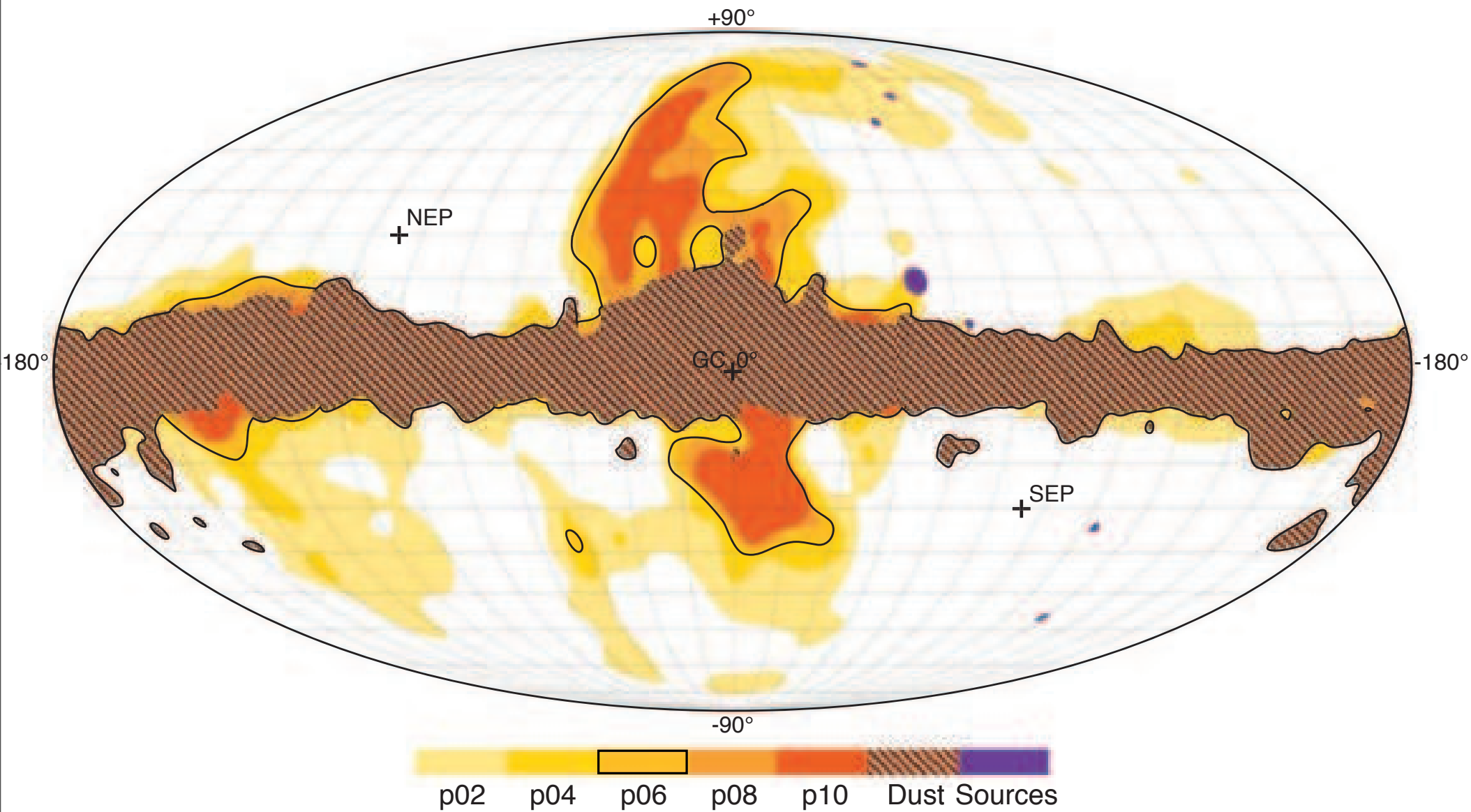
V band - 61 GHz



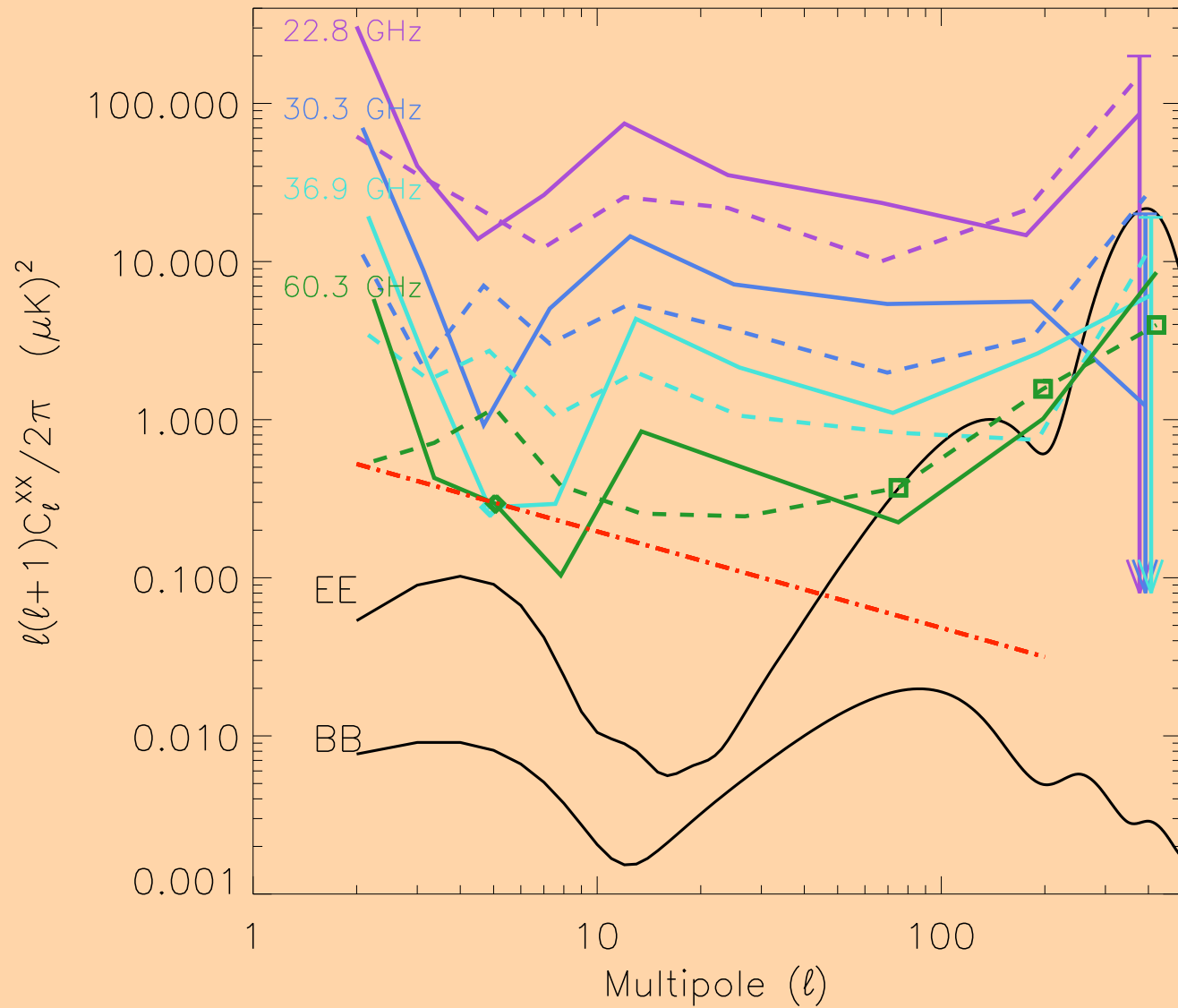
W band - 94 GHz



Polarization mask



Uncleaned power spectra



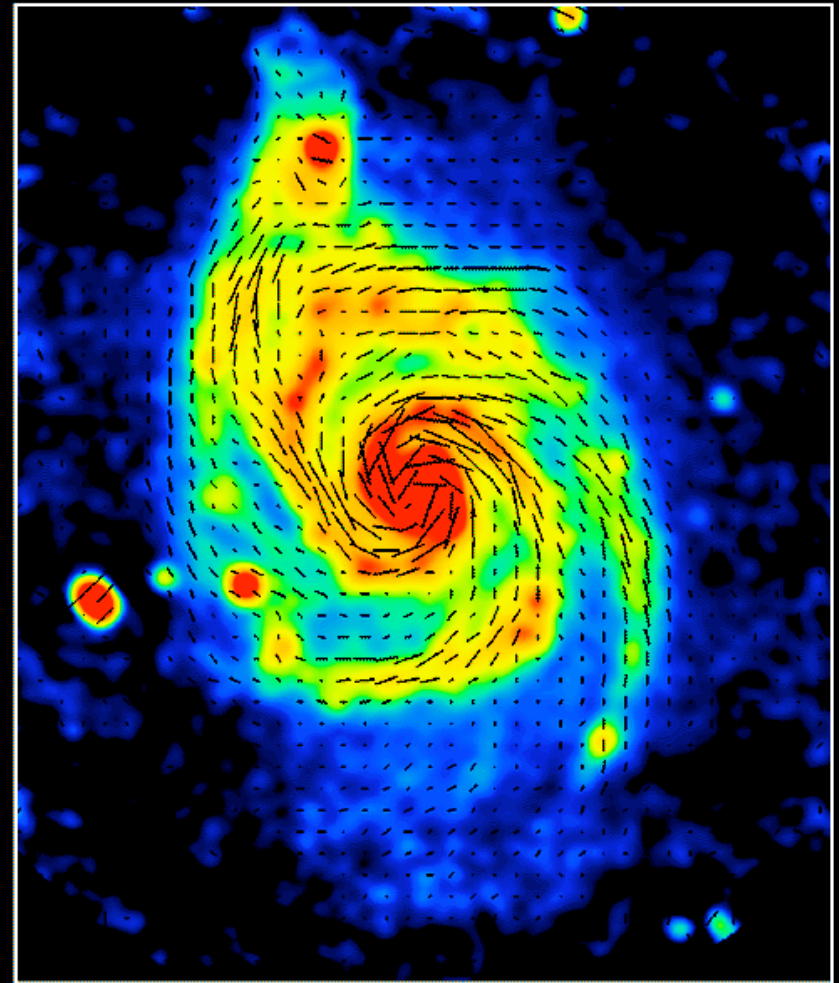
Foregrounds dominate over all ℓ of interest and all frequencies unlike for temperature

Outside p06 mask

Spiral magnetic field structures seen in external galaxies

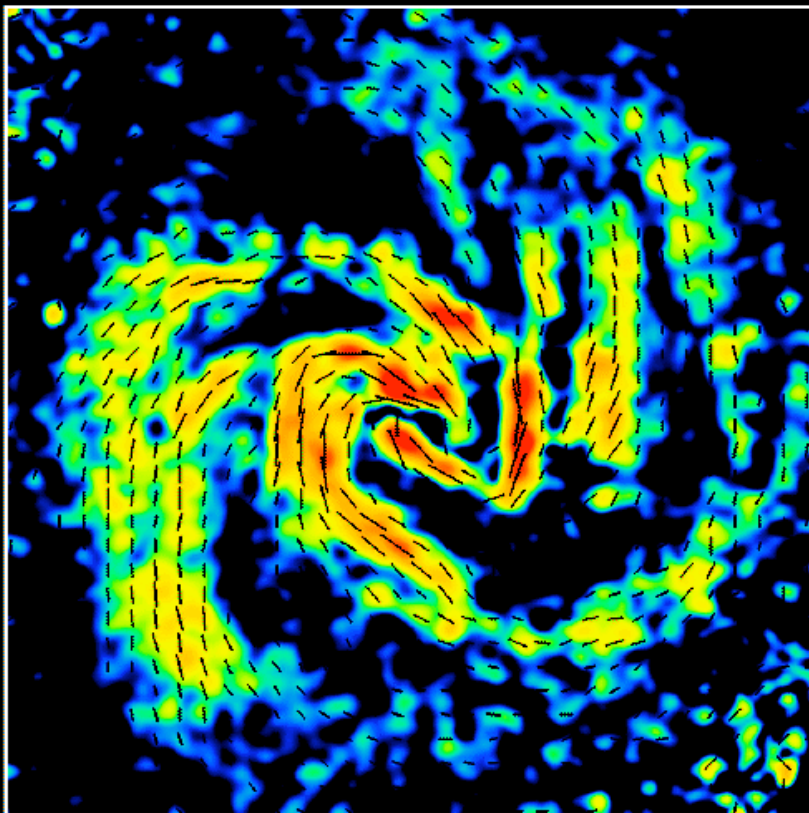
Bi-symmetric Spiral model

M51 6cm Total Int. + B-Vectors (VLA+Effelsberg)



Copyright: MPIfR Bonn (R.Beck, C.Horellou & N.Neininger)

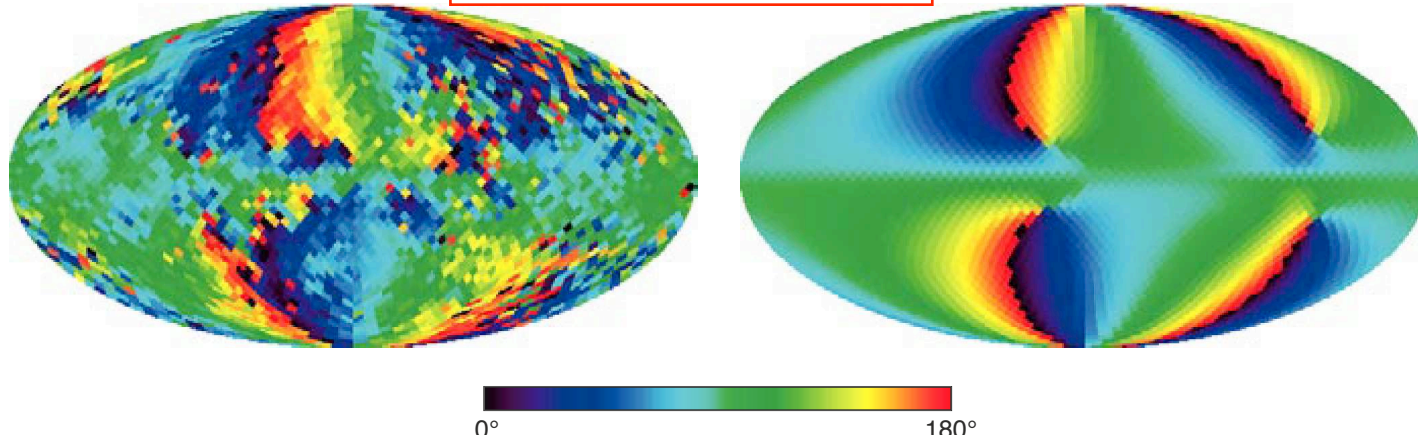
M83 6cm Polarized Int. + B-Vectors (VLA+Effelsberg)



Copyright: MPIfR Bonn (R.Beck, N.Neininger, S.Sukumar & R.Allen)

Polarized foregrounds predictions: synchrotron radiation

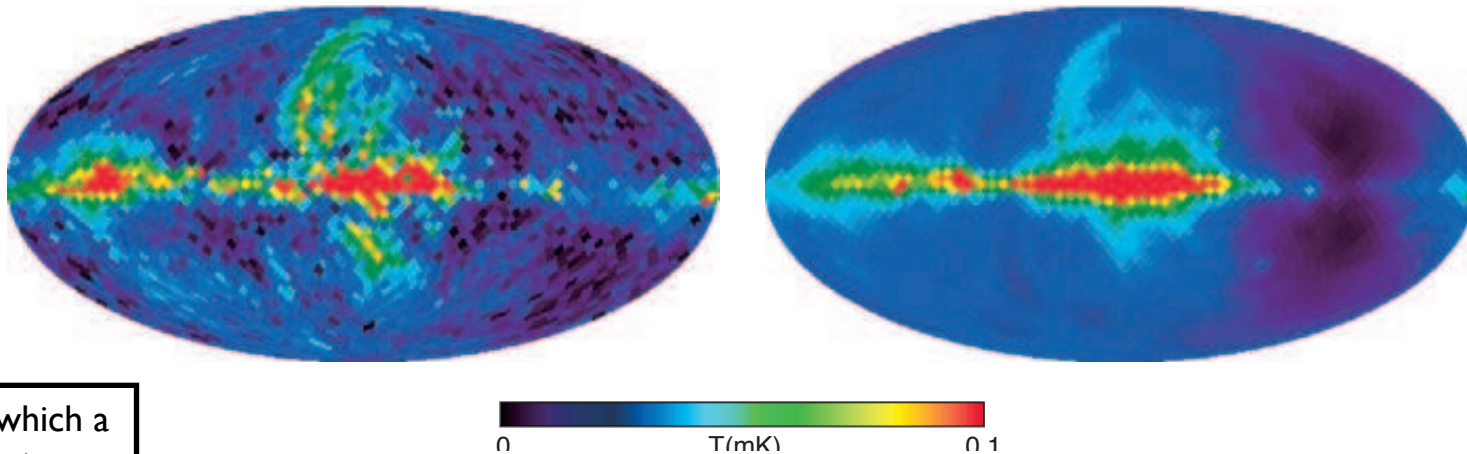
Polarization directions



Polarization amplitude

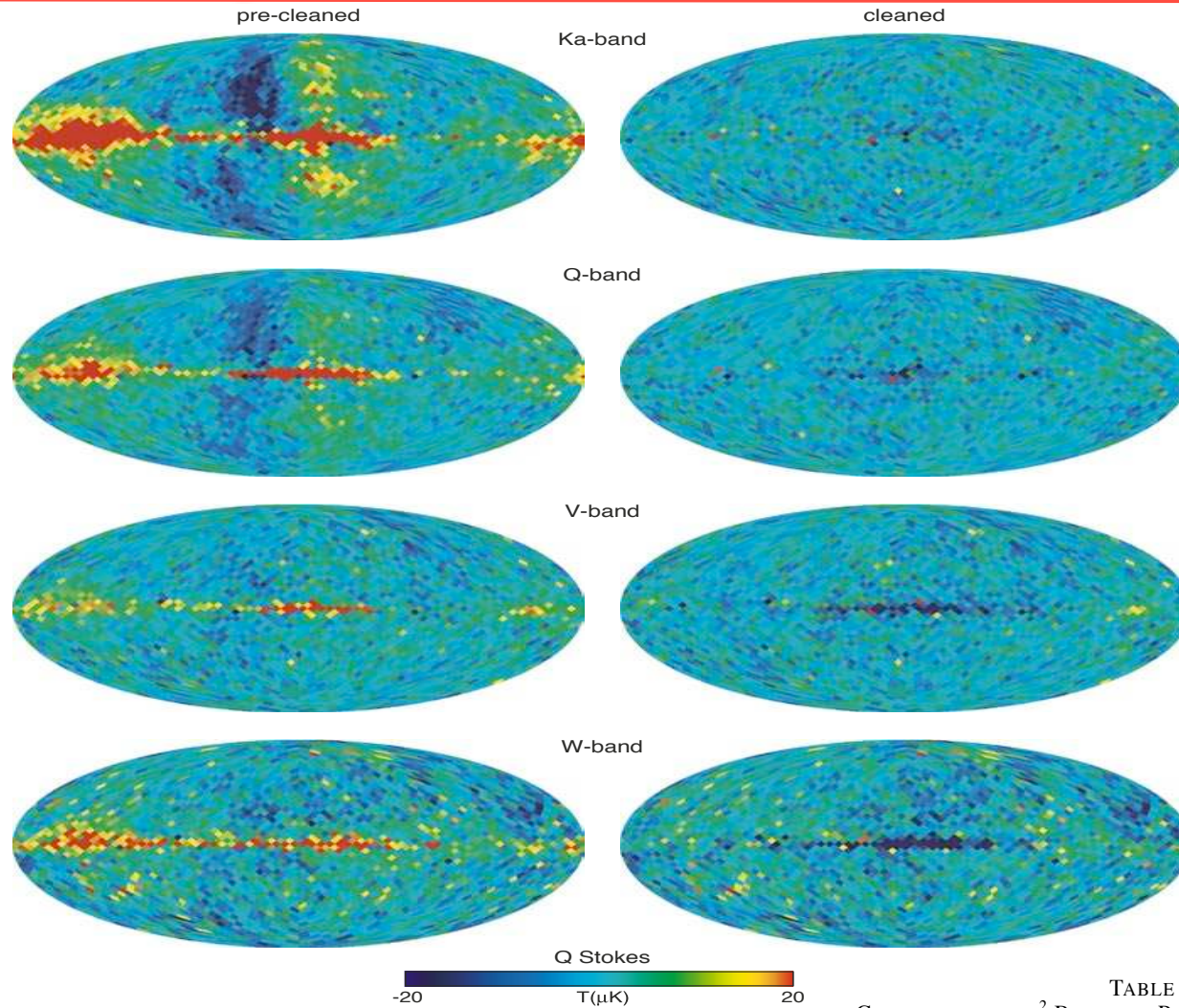
K1 Polarization Amplitude

K1 Polarization Prediction from Haslam



Based on a model in which a gas of cosmic rays electrons interact with a magnetic field following a bisymmetric spiral arm pattern

Foreground cleaned maps

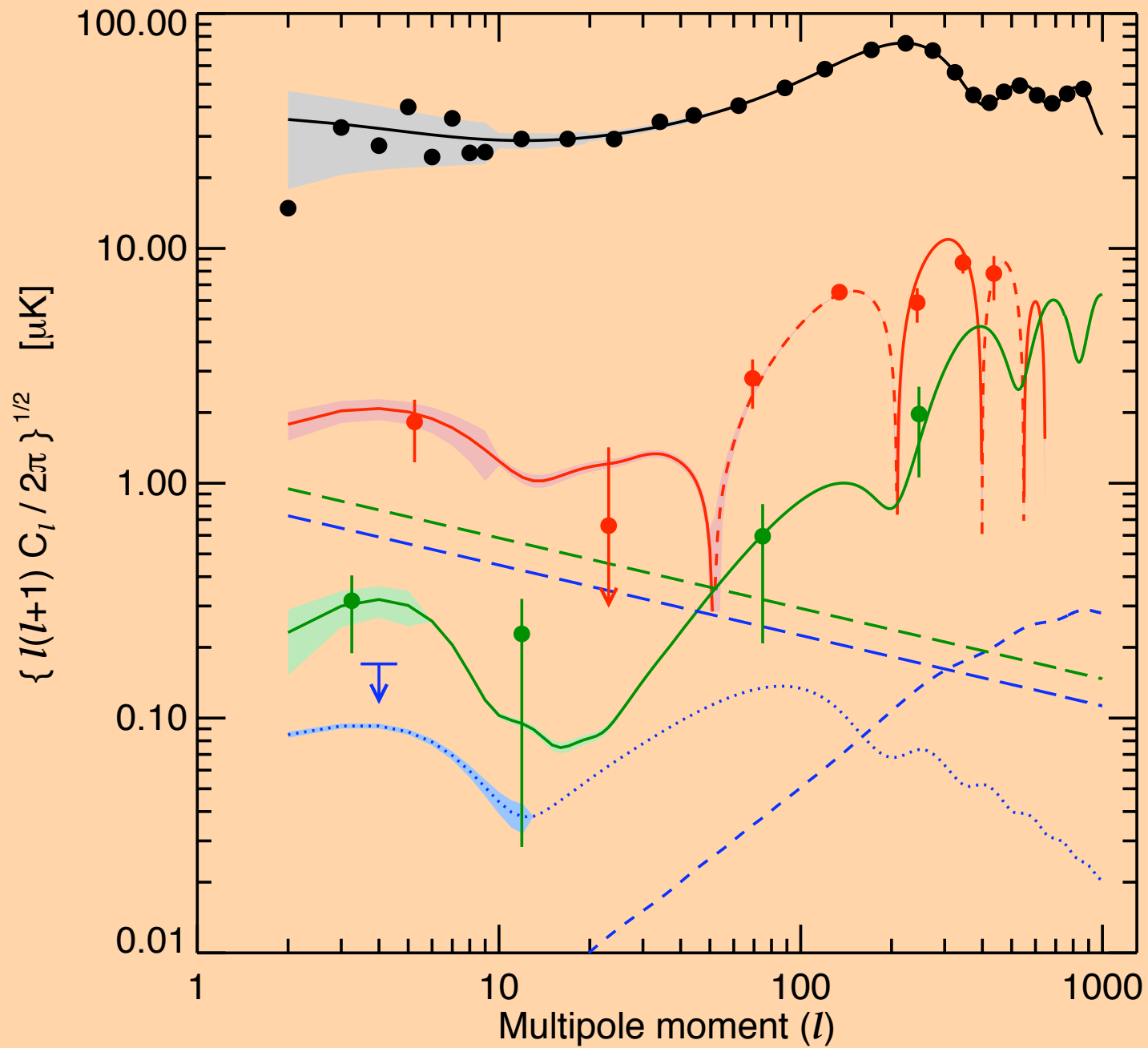


- Due to correlations between foregrounds, a map based cleaning is more powerful
- 2 parameters/frequency fit only

TABLE 4
COMPARISON OF χ^2 BETWEEN PRE-CLEANED AND CLEANED MAPS

Band	χ^2/ν Pre-cleaned	χ^2/ν Cleaned	ν	$\Delta\chi^2$
Ka	10.65	1.20	6144	58061
Q	3.91	1.09	6144	17326
V	1.36	1.19	6144	1045
W	1.38	1.58	6144	-1229
Ka	2.142	1.096	4534	4743
Q	1.289	1.018	4534	1229
V	1.048	1.016	4534	145
W	1.061	1.050	4534	50

Final CMB spectra



Cosmological Implications

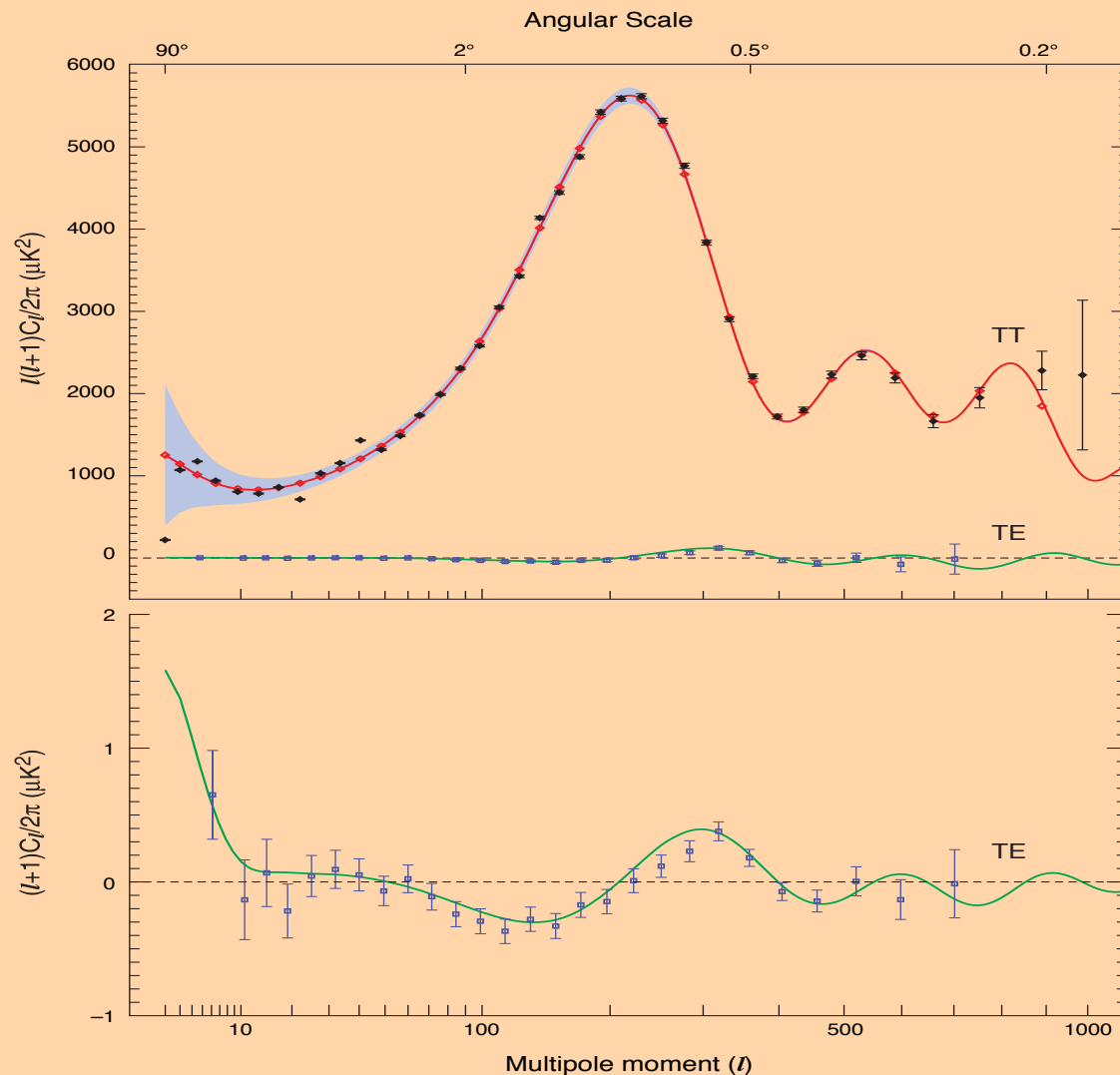
Simple Λ CDM model fits

■ Simple flat Λ CDM model with 6 parameters ($\Omega_{\text{cdm}}, \Omega_{\text{b}}, n_{\text{s}}, A_{\text{s}}, h, \tau$) still an excellent fit

■ Despite smaller error bars, the χ^2_{eff} for TT improves from 1.09 (893 dof) to 1.068 (982 dof) and from 1.066 (1342 dof) to 1.041 for TT+TE (1410 dof)

■ For T, Q, U maps, we have $\chi^2_{\text{eff}}=0.981$ for 1838 pixels

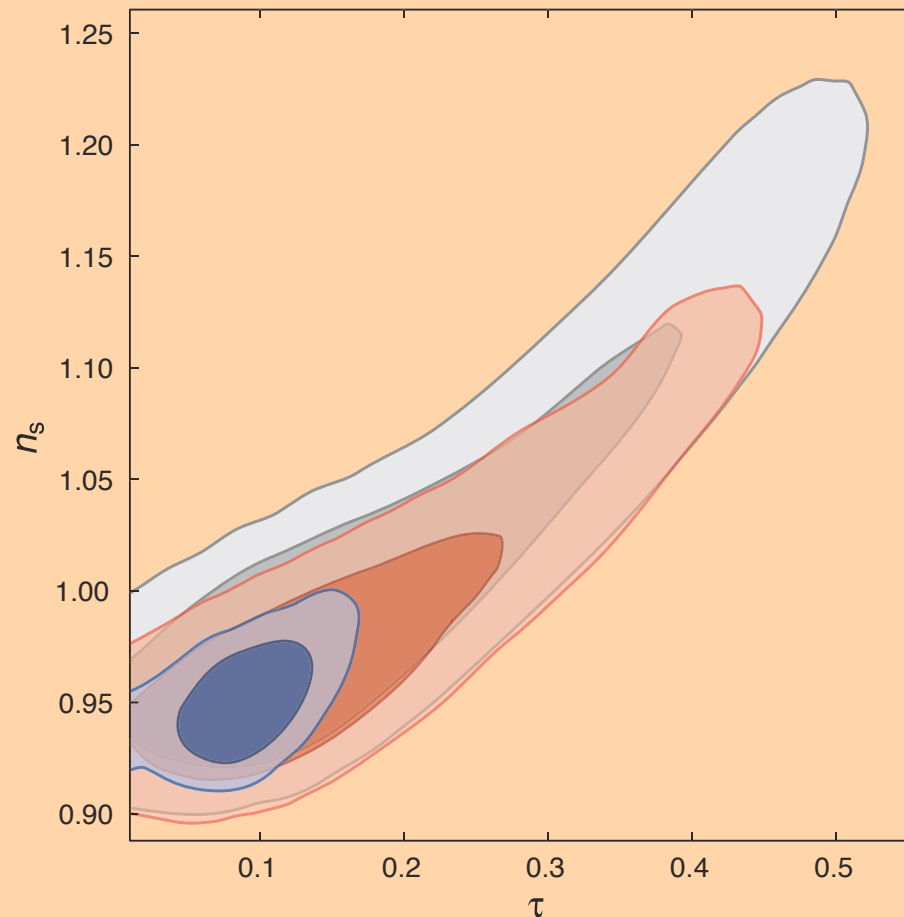
■ Previously discrepant points get closer



Improvement in parameter space

Parameter	First Year ML	WMAPext ML	Three Year ML
$100\Omega_b h^2$	2.30	2.21	2.22
$\Omega_m h^2$	0.145	0.138	0.128
H_0	68	71	73
τ	0.10	0.10	0.092
n_s	0.97	0.96	0.958
Ω_m	0.32	0.27	0.24
σ_8	0.88	0.82	0.77

First Year Mean	WMAPext Mean	Three Year Mean
$2.38^{+0.13}_{-0.12}$	$2.32^{+0.12}_{-0.11}$	2.23 ± 0.08
$0.144^{+0.016}_{-0.016}$	$0.134^{+0.006}_{-0.006}$	0.126 ± 0.009
72^{+5}_{-5}	73^{+3}_{-3}	74^{+3}_{-3}
$0.17^{+0.08}_{-0.07}$	$0.15^{+0.07}_{-0.07}$	0.093 ± 0.029
$0.99^{+0.04}_{-0.04}$	$0.98^{+0.03}_{-0.03}$	0.961 ± 0.017
$0.29^{+0.07}_{-0.07}$	$0.25^{+0.03}_{-0.03}$	0.234 ± 0.035
$0.92^{+0.1}_{-0.1}$	$0.84^{+0.06}_{-0.06}$	0.76 ± 0.05

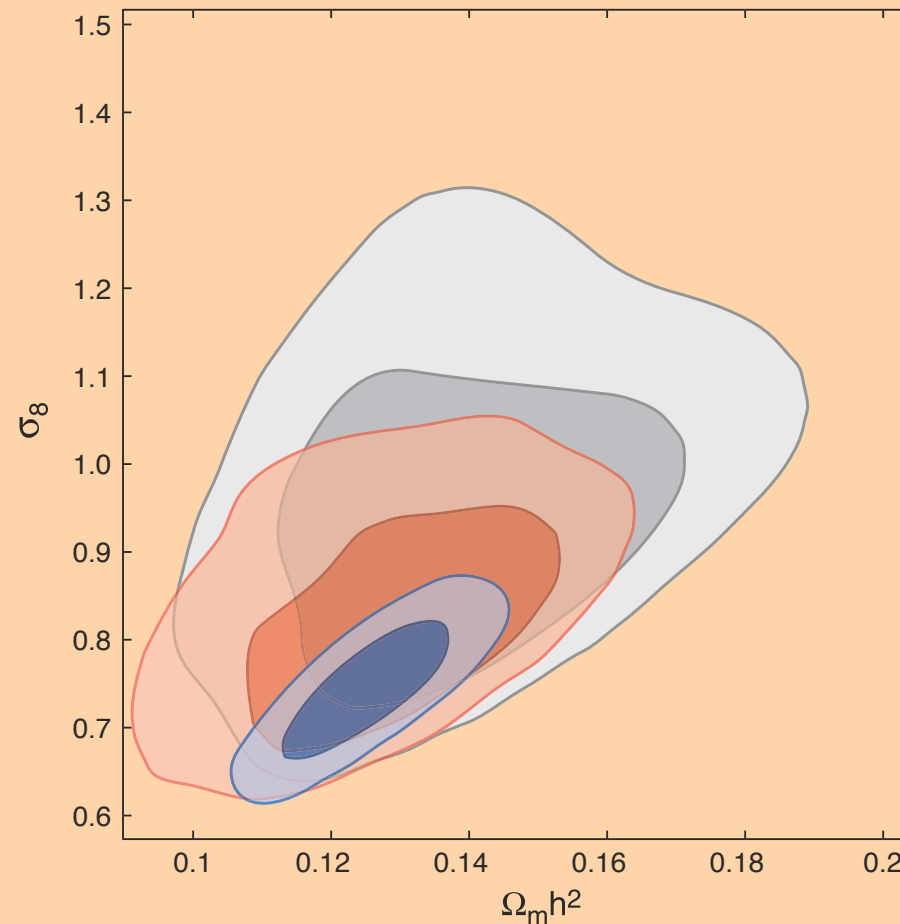


Driven by EE

Improvement in parameter space

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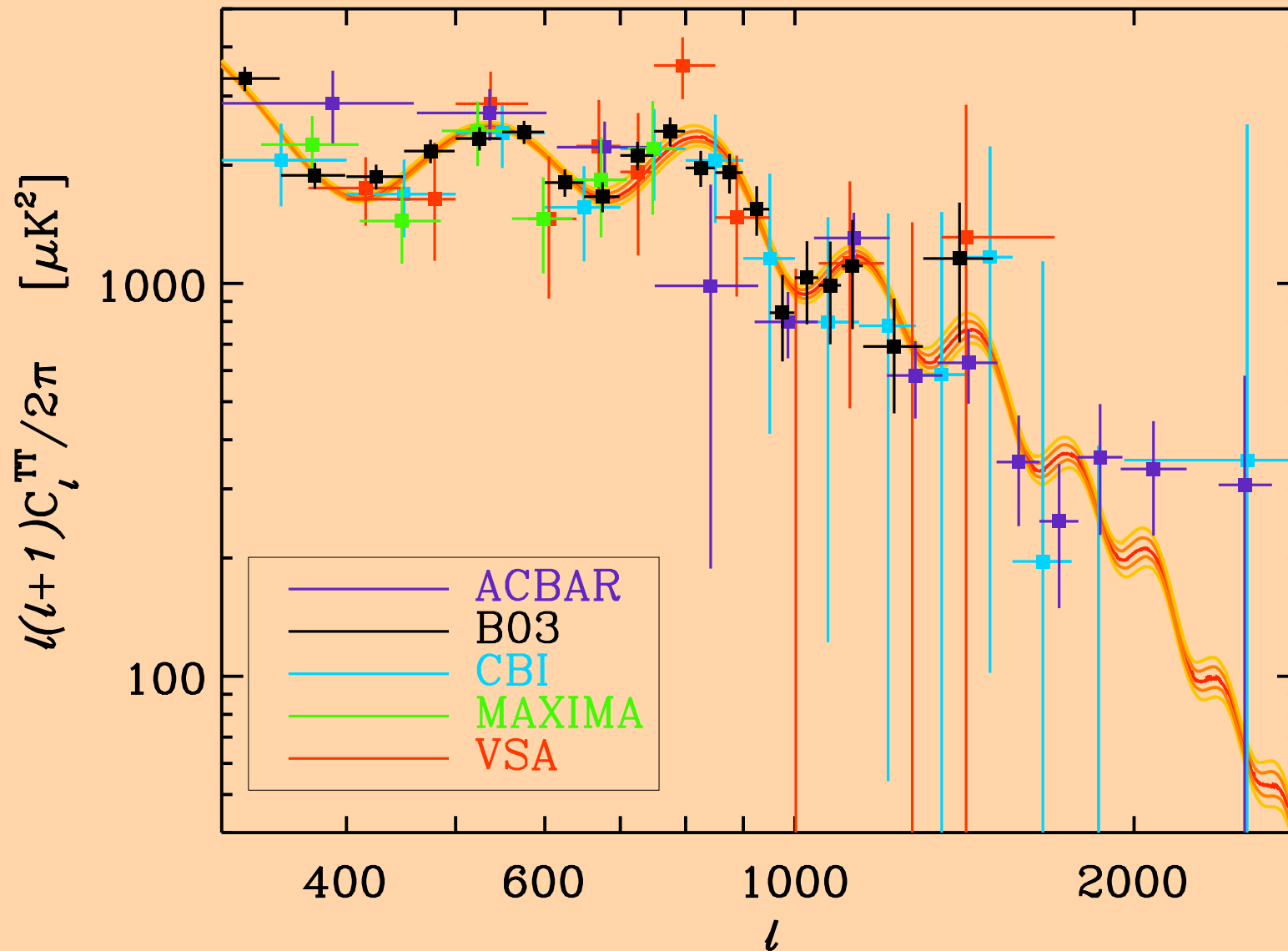


Driven by 3^d peak

τ is robust vs foregrounds!

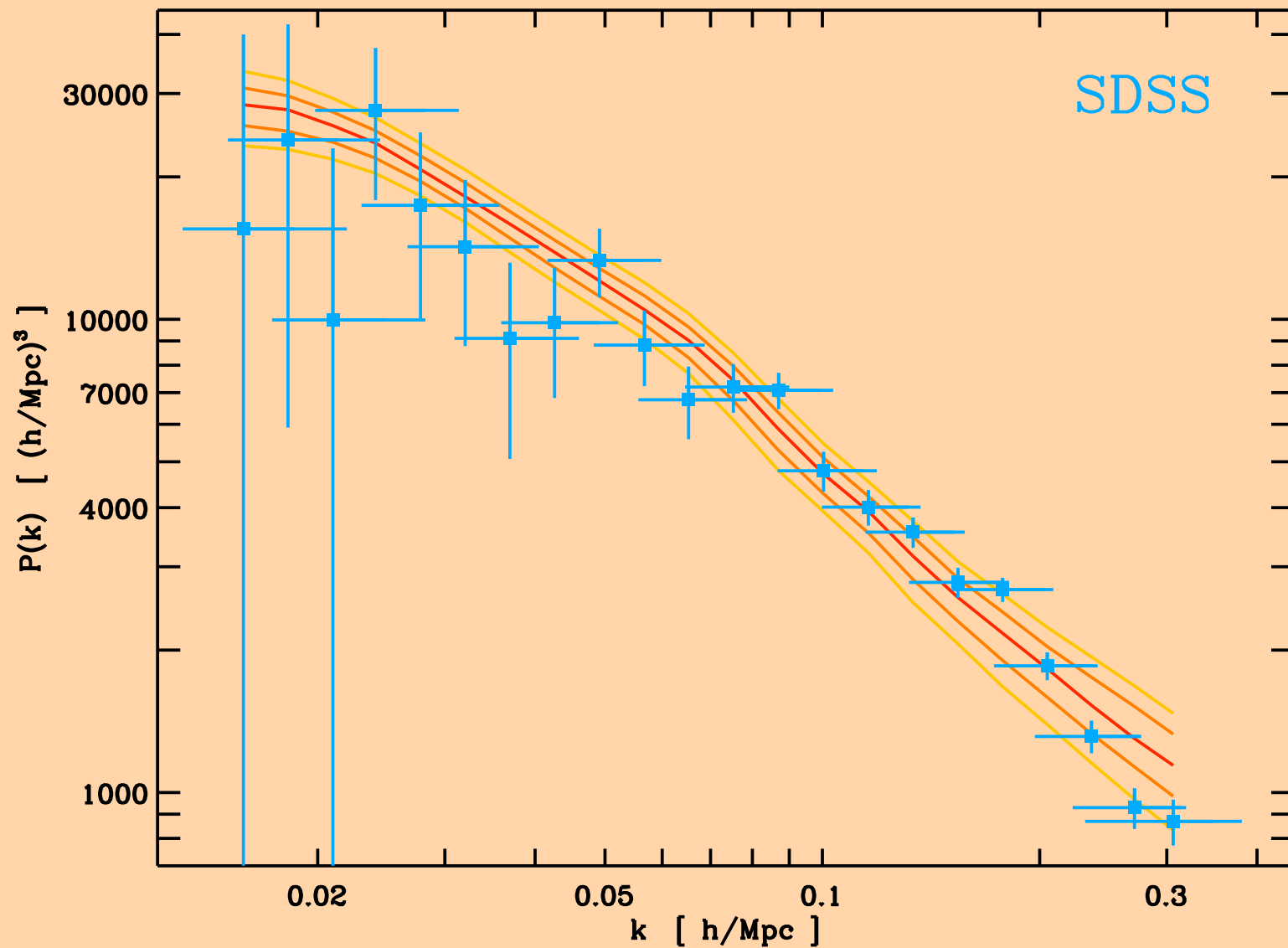
Combination	Exact EE Only	Exact EE & TE
KaQV	0.111 ± 0.022	0.111 ± 0.022
Q	0.100 ± 0.044	0.082 ± 0.043
QV	0.100 ± 0.029	0.092 ± 0.029
QV+VV
V	0.089 ± 0.048	0.094 ± 0.043
QVW	0.110 ± 0.021	0.101 ± 0.023
KaQVW	0.107 ± 0.018	0.106 ± 0.019

Cosmological contrasts... and yet concordance



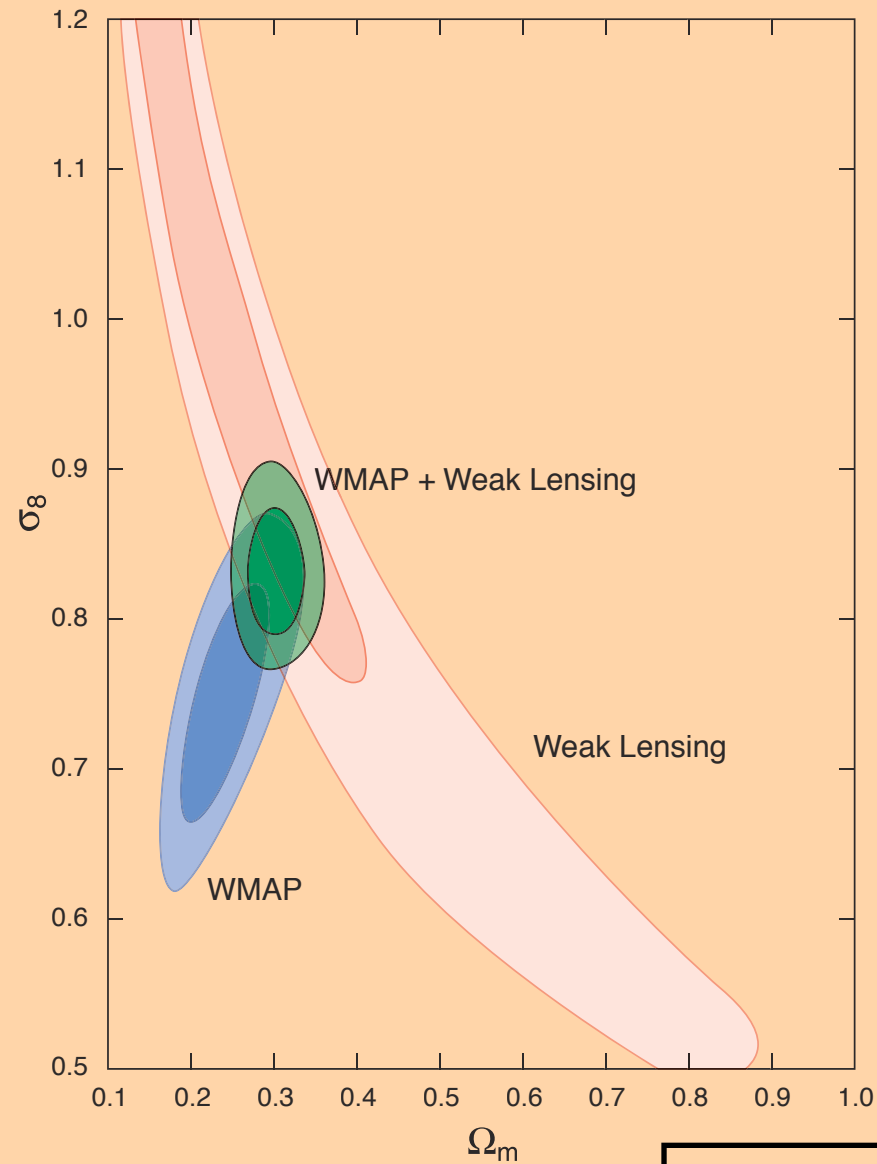
WMAP “predicts” small scale CMB experiments

Cosmological contrasts... and yet concordance



WMAP “predicts” low z mass distribution
(same for 2dF)

Weak-lensing joint analysis



Weak lensing really starts to hold its promises even if slight tension here

CFHTLS current analysis
22 sq degree
Down to a magnitude $i' = 24.5$

Hoekstra et al. 05
Sembolini et al. 05

Where are we now?

The current “phenomenological” success means:

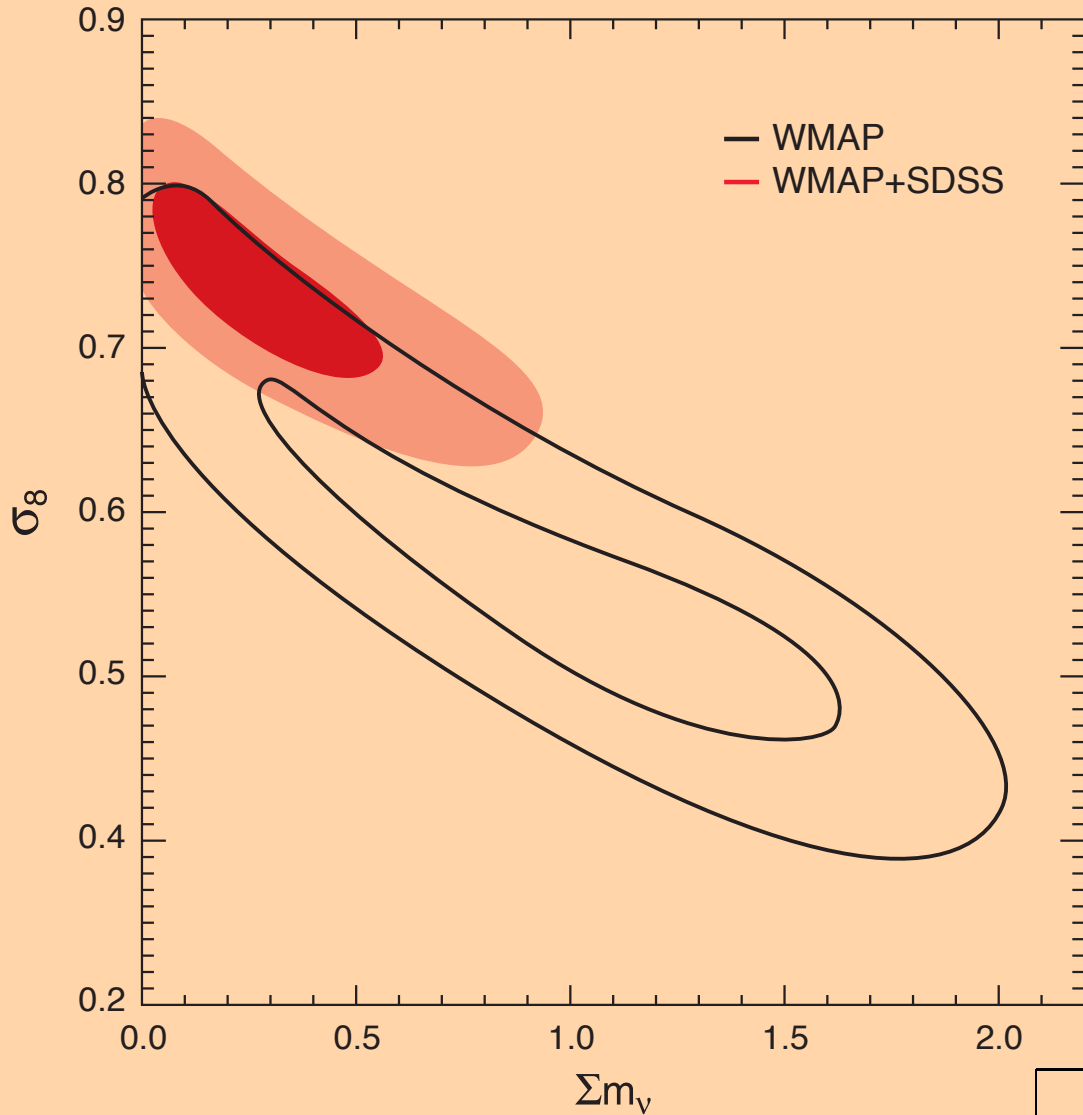
- The primordial inhomogeneities are mostly adiabatic with a nearly scale invariant power spectrum
- We have a successful GR based theory of linear perturbations to evolve them
- We have a good description of the main components even if we do not know what they are

We can now ask various sets of questions:

- Ask question within the model
 - What else can we learn about the components of the model, eg neutrino?
 - What is Dark Energy?
 - What is Dark Matter?
 - Did the Universe really undergo an Inflationary phase?
 - First stars and how did the Universe get reionized?
- Explore further the data and look for “anomalies”, ie deviations from this model

Physics we don't know yet
Fundamental
Physics we don't know to compute

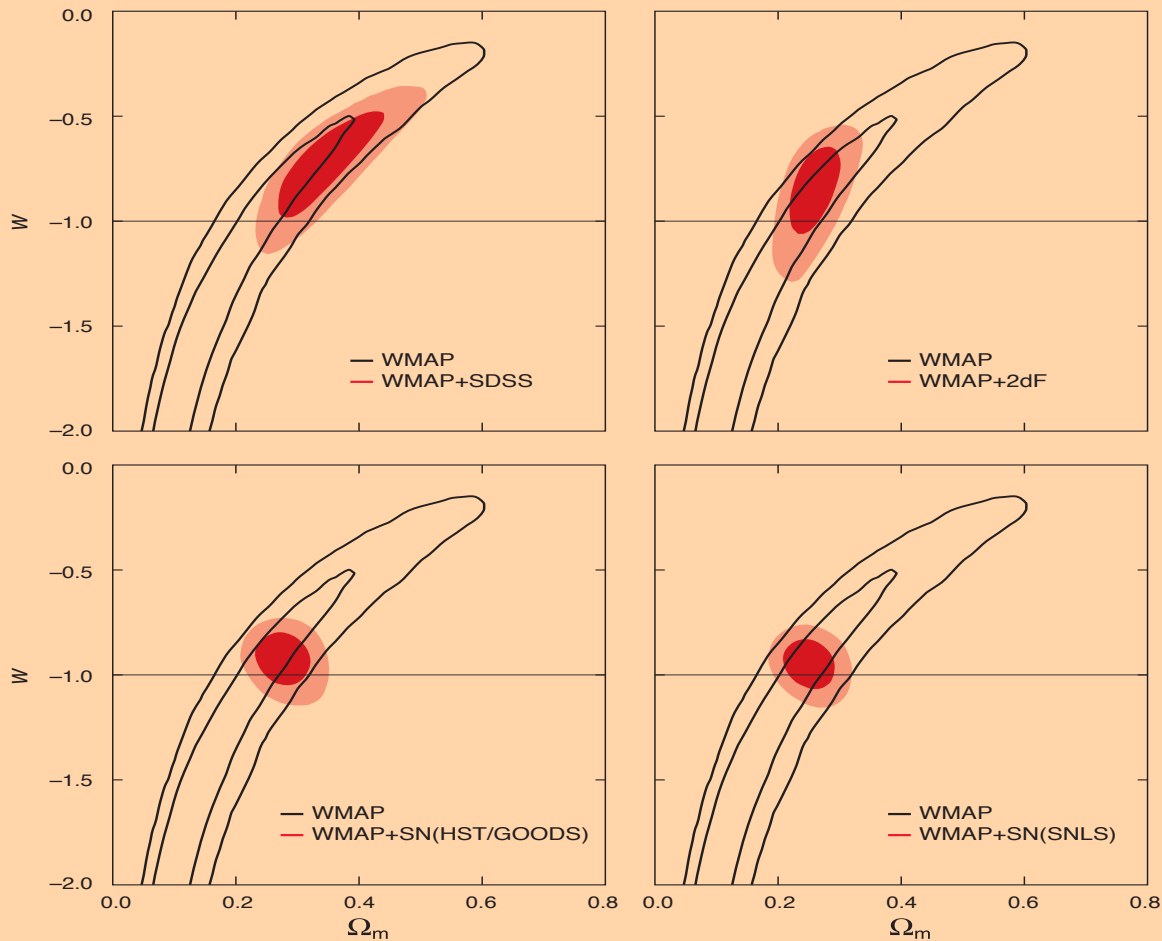
Constraining neutrino mass



Data Set	Σm_ν (95% limit for $N_\nu = 3.02$)
WMAP	2.0 eV(95% CL)
WMAP + SDSS	0.91 eV(95% CL)
WMAP + 2dFGRS	0.87 eV(95% CL)
CMB + LSS + SN	0.68 eV(95% CL)

Dark Energy

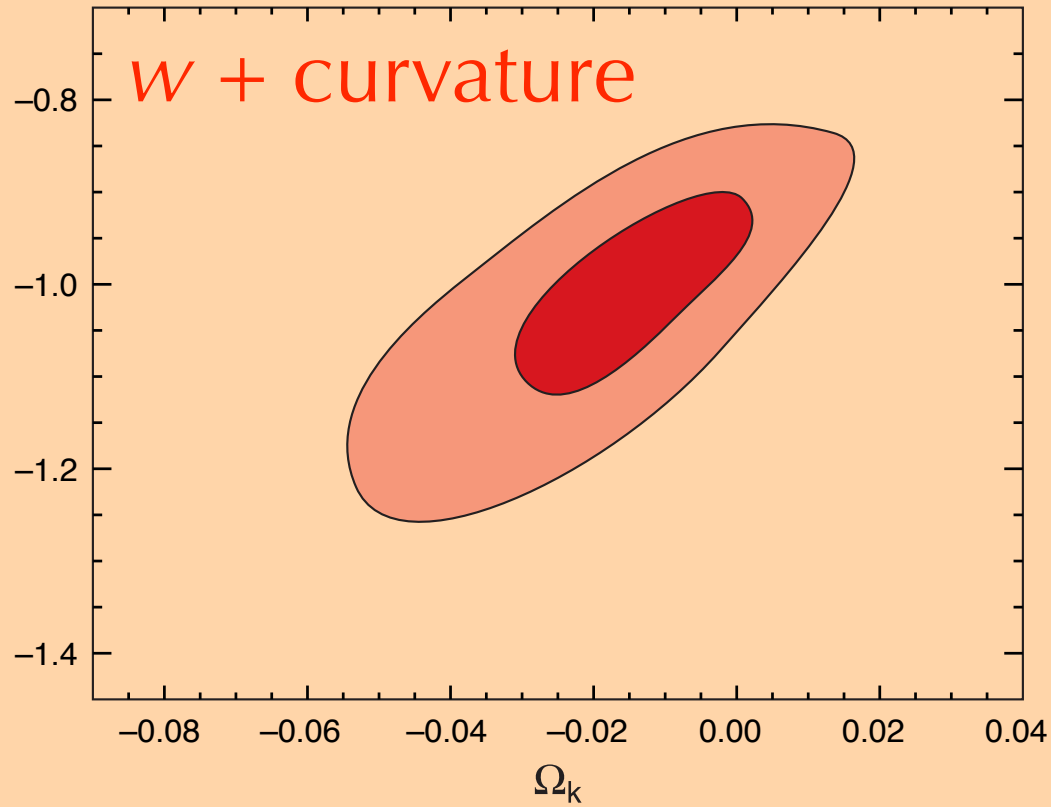
Constraints on constant DE equation of state $w=p/\rho$



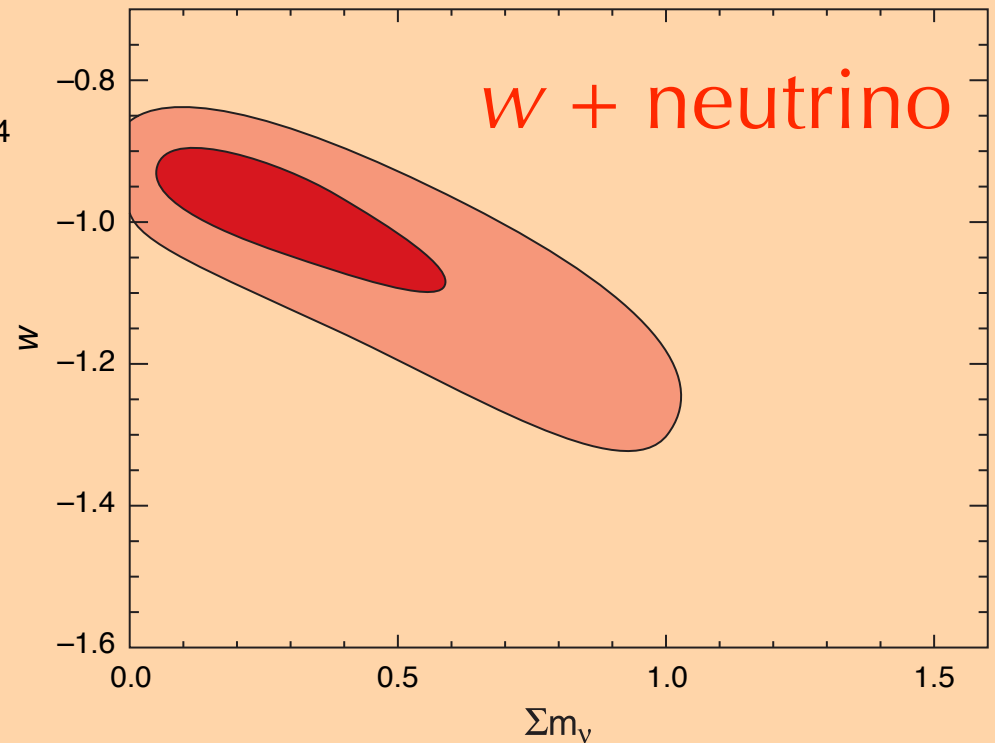
With DE perturbations
but fixed c_s^2 (cf Bean & Doré 03)

Data Set	with perturbations
WMAP + SDSS	$-0.75^{+0.18}_{-0.16}$
WMAP + 2dFGRS	$-0.914^{+0.193}_{-0.099}$
WMAP + SNGold	$-0.944^{+0.076}_{-0.094}$
WMAP + SNLS	$-0.966^{+0.070}_{-0.090}$
CMB+ LSS+ SN	$-0.926^{+0.051}_{-0.075}$

Robustness of DE constraints



CMB + LSS + SN



What is Inflation?

- Inflation was introduced to solve the problems of the “standard Big Bang” model like *flatness* and the *horizon problem*
- **Key feature:** during an extended period of time, the universe is expanding exponentially. Fluctuations are generated during this phase
- This is achieved by introducing in the matter sector (a) new scalar field(s) ϕ with a well chosen potential $V(\phi)$
- For a given $V(\phi)$ there are relations between derivatives of V and observables like n_s , r and $dn_s/d\ln k$
- Testing Inflation is mostly testing these consistency relations

What are Inflation predictions?

Most of Inflation predictions, in the 80s, when there were few evidences for any of those idea

- **Flatness** \Rightarrow *TOCO, MAXIMA, BOOMERANG, WMAP...*
- **Primordial perturbations nearly scale invariant** \Rightarrow *COBE ($n_s = 1.2 \pm 0.3$ - Gorski et al. 96)*
- **Gaussianity of fluctuations** \Rightarrow *WMAP-1*
- **Adiabatic initial perturbations** \Rightarrow *WMAP-1*
- **Super-Horizon perturbations** \Rightarrow *WMAP-1 (TE at $l \sim 100$)*
- **Deviation from scale invariance** \Rightarrow *WMAP-3*
- **Tensor perturbations, i.e. Gravity Wave Background** \Rightarrow *WMAP-8 ?, Planck?, Spider?, Biceps?*

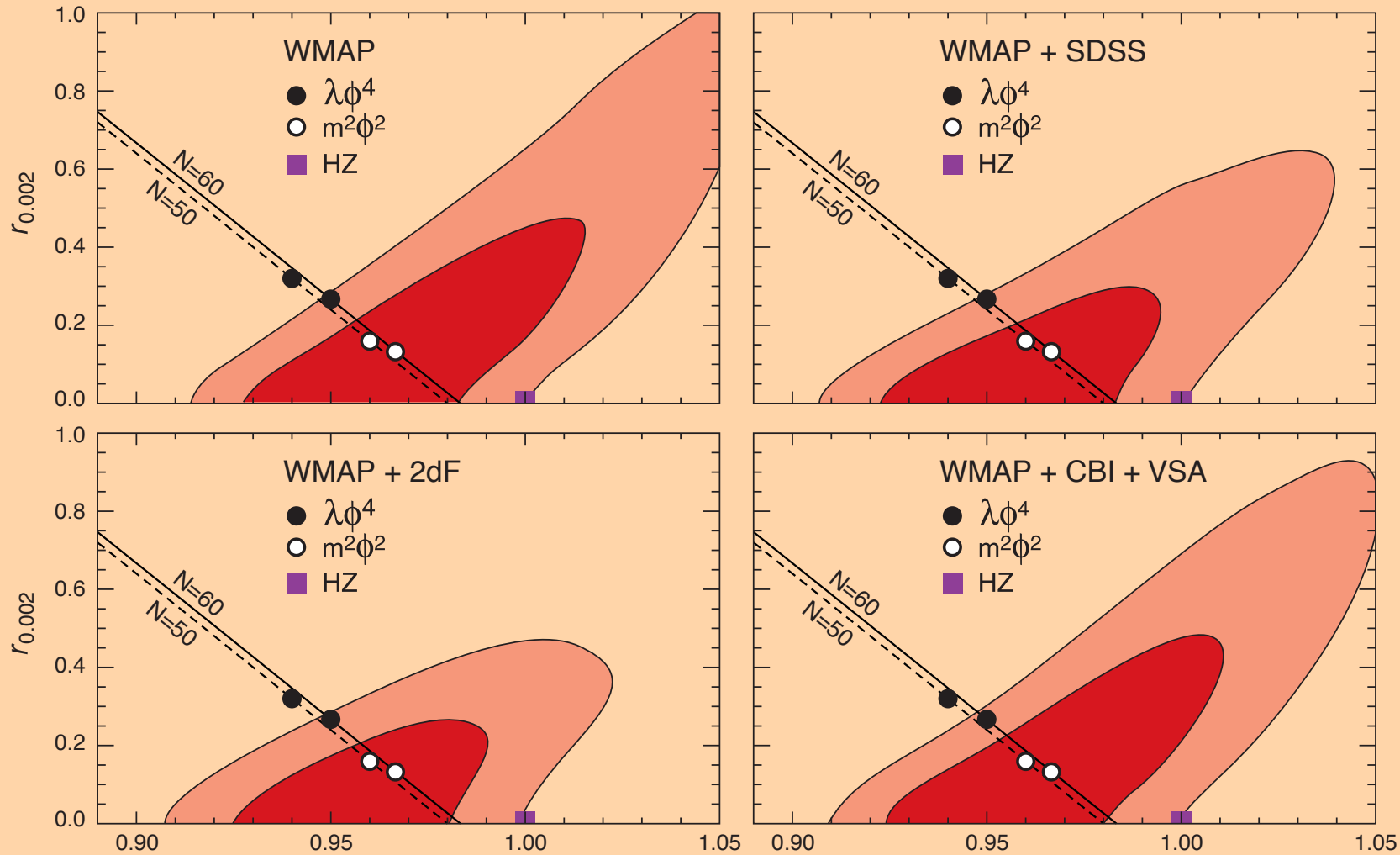
Spectral index, tensor modes and Inflation

$V(\phi) \propto \phi^\alpha$ Consistency relations

$$r \simeq \frac{4\alpha}{N}$$

$$1 - n_s = \frac{\alpha + 2}{2N}$$

where $\Delta_R^2(k) = \left(\frac{k}{k_0}\right)^{n_s-1}$

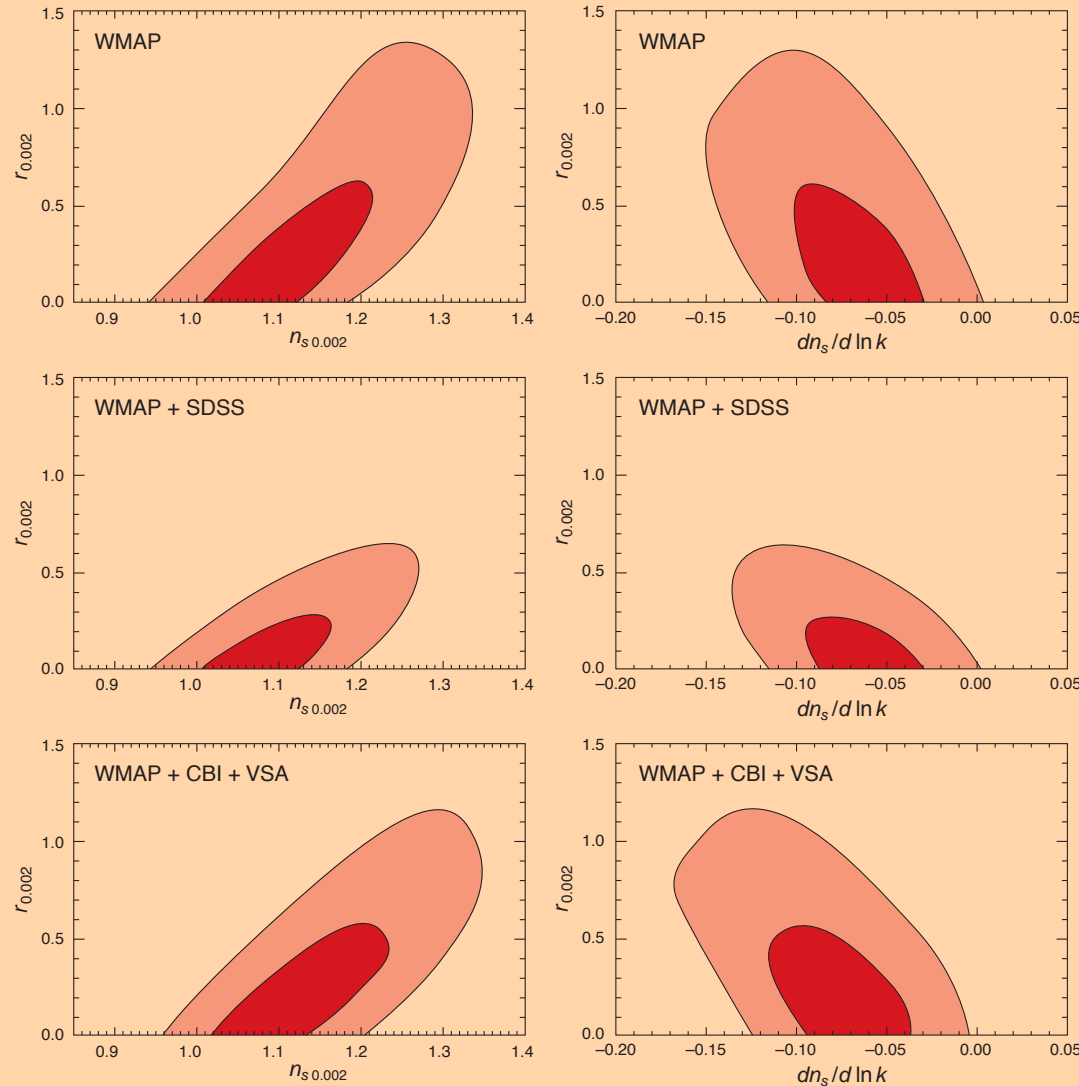


Similar constraints for B03+ACBAR

These models predict almost no running

Do we see a running spectral index?

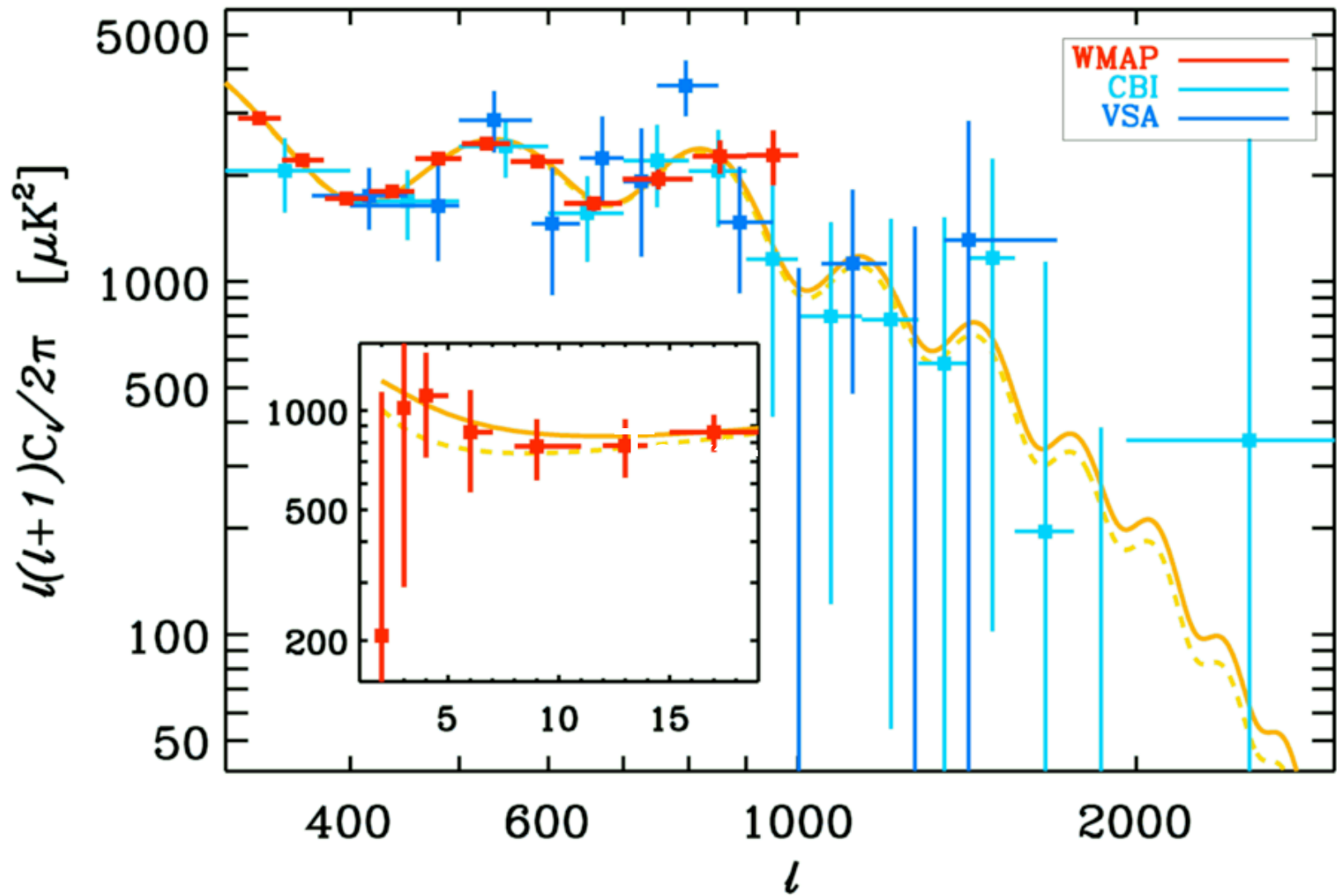
$$\frac{d \ln \Delta_R^2(k)}{d \ln k} = n_s(k_0) - 1 + \frac{dn_s}{d \ln k} \ln(k/k_0)$$



Similar constraints for B03+ACBAR

- Consistent trend but weak signal so far
- WMAP and LSS probe almost the same scales currently
- The trends come ~equally from the low l points and the high l points

Where do these constraints come from?



The constraints come almost equally from the lowest l and the highest l

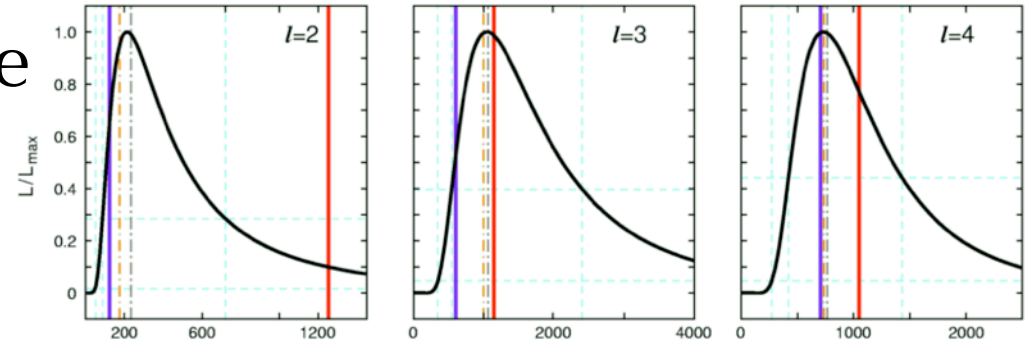
Large scale temperature fluctuations

■ Low COBE-WMAP quadrupole

Efstathiou 04

Slozar *et al.* 04

Bielewicz *et al.* 04



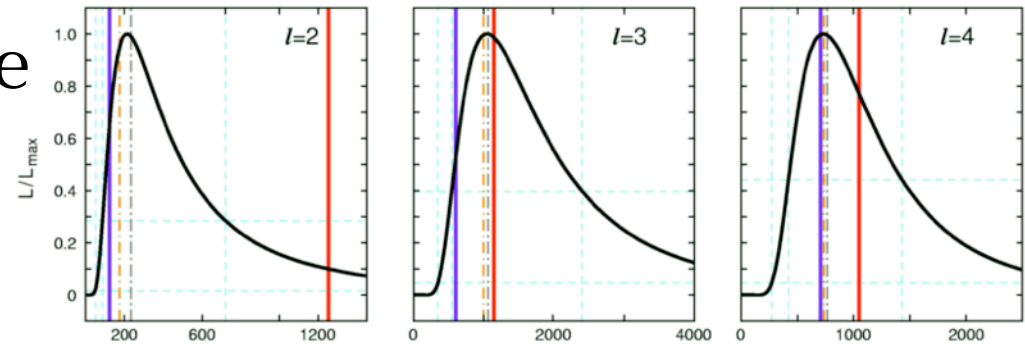
Large scale temperature fluctuations

Low COBE-WMAP quadrupole

Efstathiou 04

Slozar *et al.* 04

Bielewicz *et al.* 04



Low l alignments

Tegmark *et al.* 04

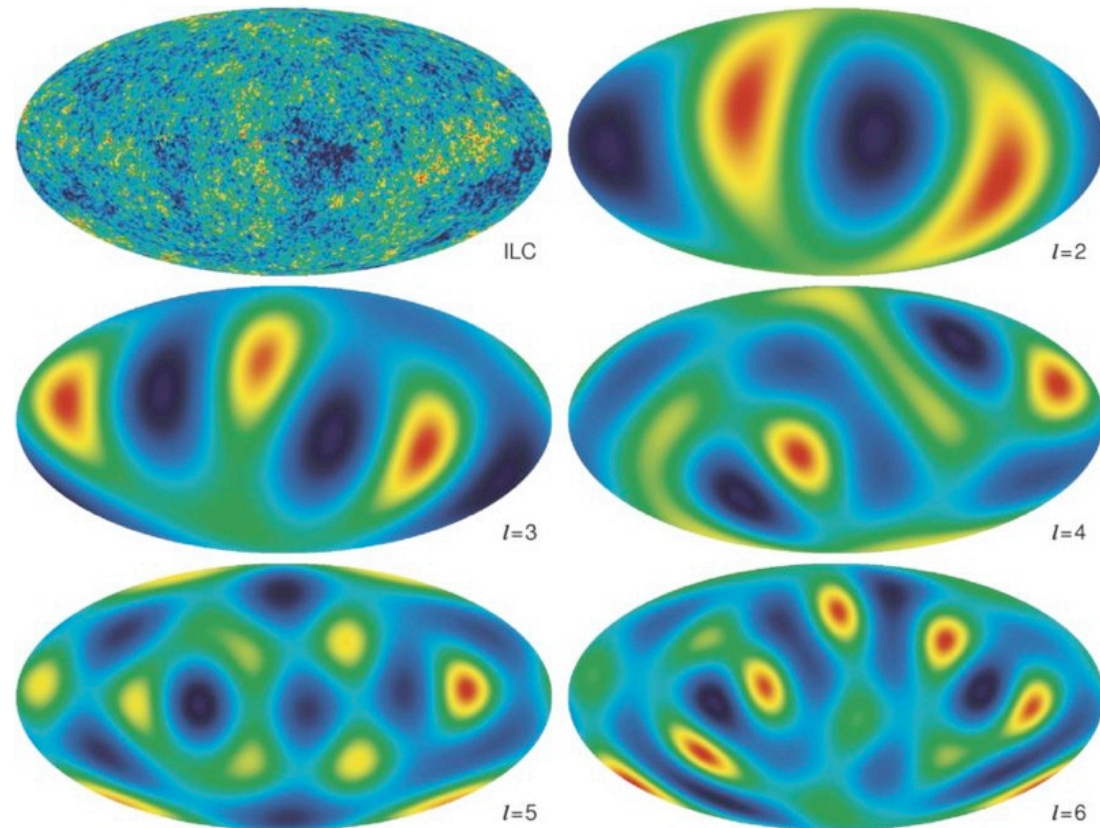
de Oliveira-Costa *et al.* 04

Eriksen *et al.* 04

Copi *et al.* 04

Land & Magueijo 04

- Low l power + alignment probability was estimated at $\sim 4 \cdot 10^{-5}$
- This result is a *posteriori* so potentially strongly biased, but also potentially significant
- The yr3 temperature maps are almost unchanged at these scales



Unchanged Temperature maps on large scales

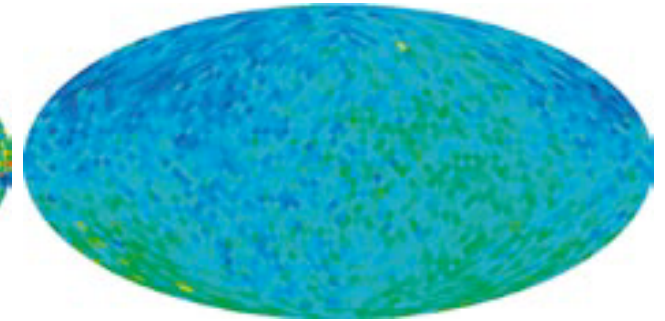
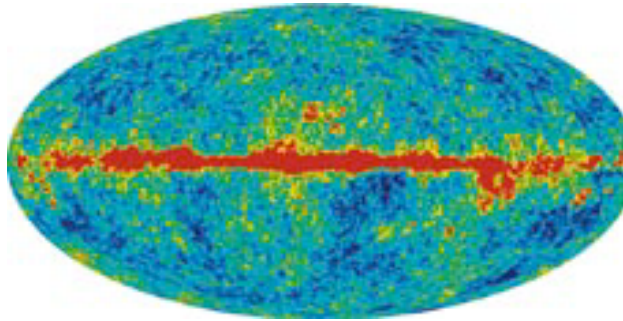
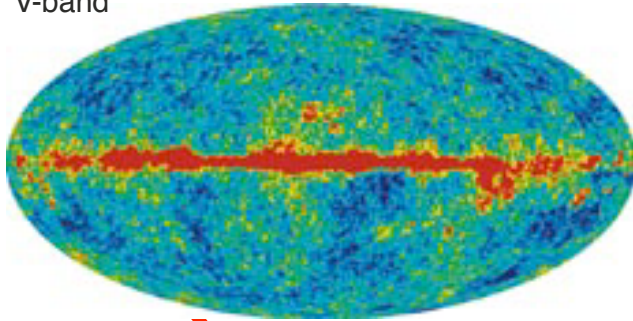
V band

year 1 (pub)

year 3

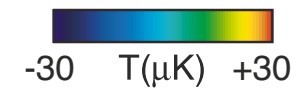
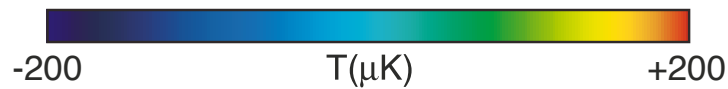
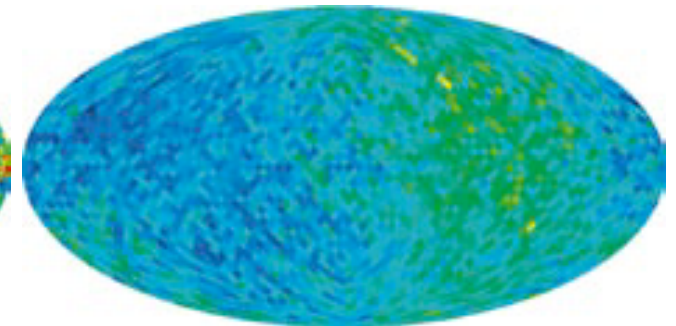
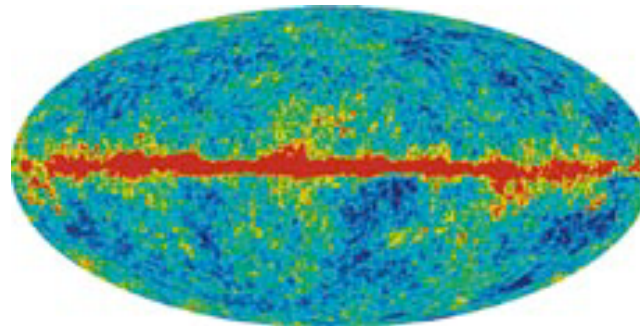
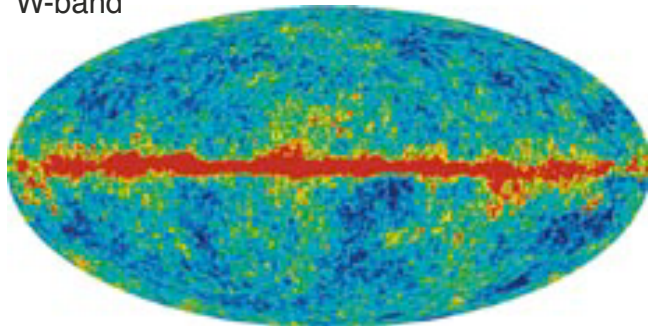
year 3 - year 1

V-band



W band

W-band



The previously mentioned analysis are very unlikely to be altered

Testing Isotropy

Large scale modulation

- We choose to address these 3 issues in a unifying manner by asking a simple question:

Can we describe the observed temperature field as a Gaussian isotropic field, T , modulated by an arbitrary (deterministic) field f ?

$$\tilde{T}(\hat{n}) = T(\hat{n})[1 + f(\hat{n})]$$

- Although the theoretical motivations are still weak, this phenomenological description is appealing since we can address and quantify in a Bayesian context the “alignment”, low l power and asymmetry simultaneously
 - $f = 0$ is the usual assumption
 - If f was dipolar, it could lead to an asymmetry and potentially to some modifications to C_l of T
 - If f was quadrupolar, it would tend to align the observed quadrupole and octopole independantly of T and alter the C_l
 - etc.

$$f(\hat{n}) = \sum_{\ell=0}^{1 \text{ or } 2} \sum_{m=-\ell}^{+\ell} f_{\ell m} Y_{\ell m}(\hat{n})$$

- We can compute the exact likelihood

$$L(\hat{T} | C_{\ell}, f_{\ell m})$$

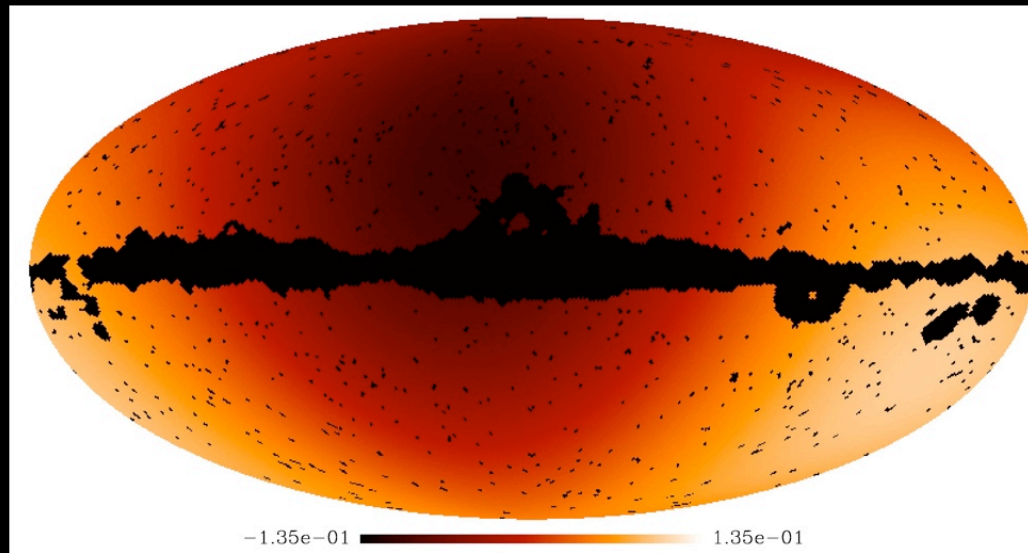
Gordon *et al.* 04
Hajian *et al.* 04
Prunet *et al.* 04
Tomita *et al.* 03

Testing Isotropy

Large scale modulation

$$\tilde{T}(\hat{n}) = T(\hat{n})[1 + f(\hat{n})]$$

f map



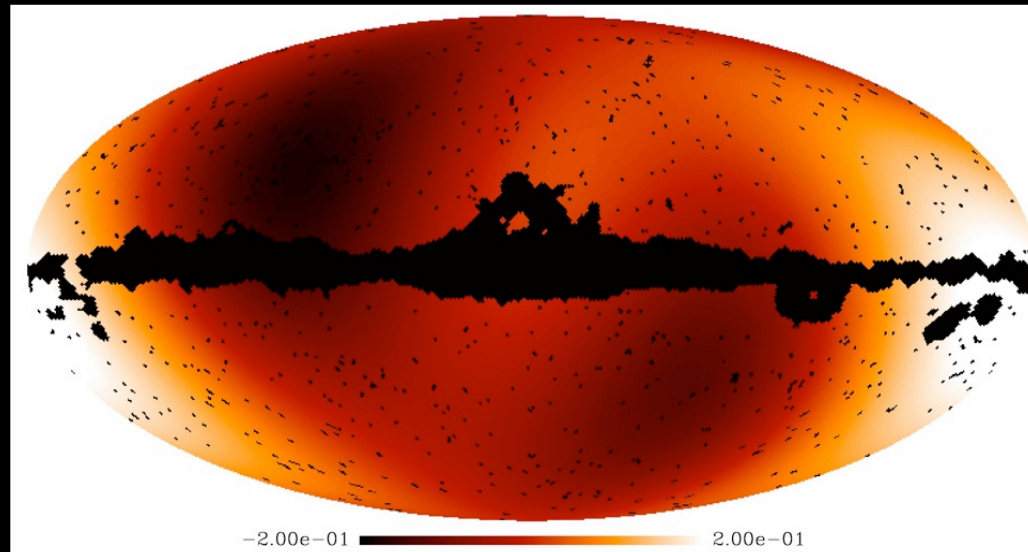
$l_{max}=1$

Testing Isotropy

Large scale modulation

$$\tilde{T}(\hat{n}) = T(\hat{n})[1 + f(\hat{n})]$$

f map



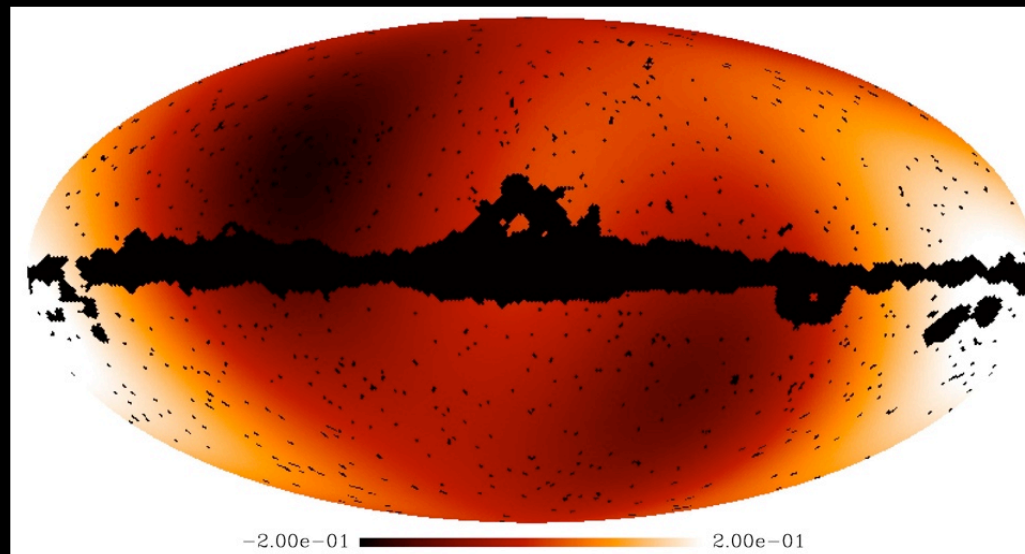
$l_{max}=2$

Testing Isotropy

Large scale modulation

$$\tilde{T}(\hat{n}) = T(\hat{n})[1 + f(\hat{n})]$$

f map



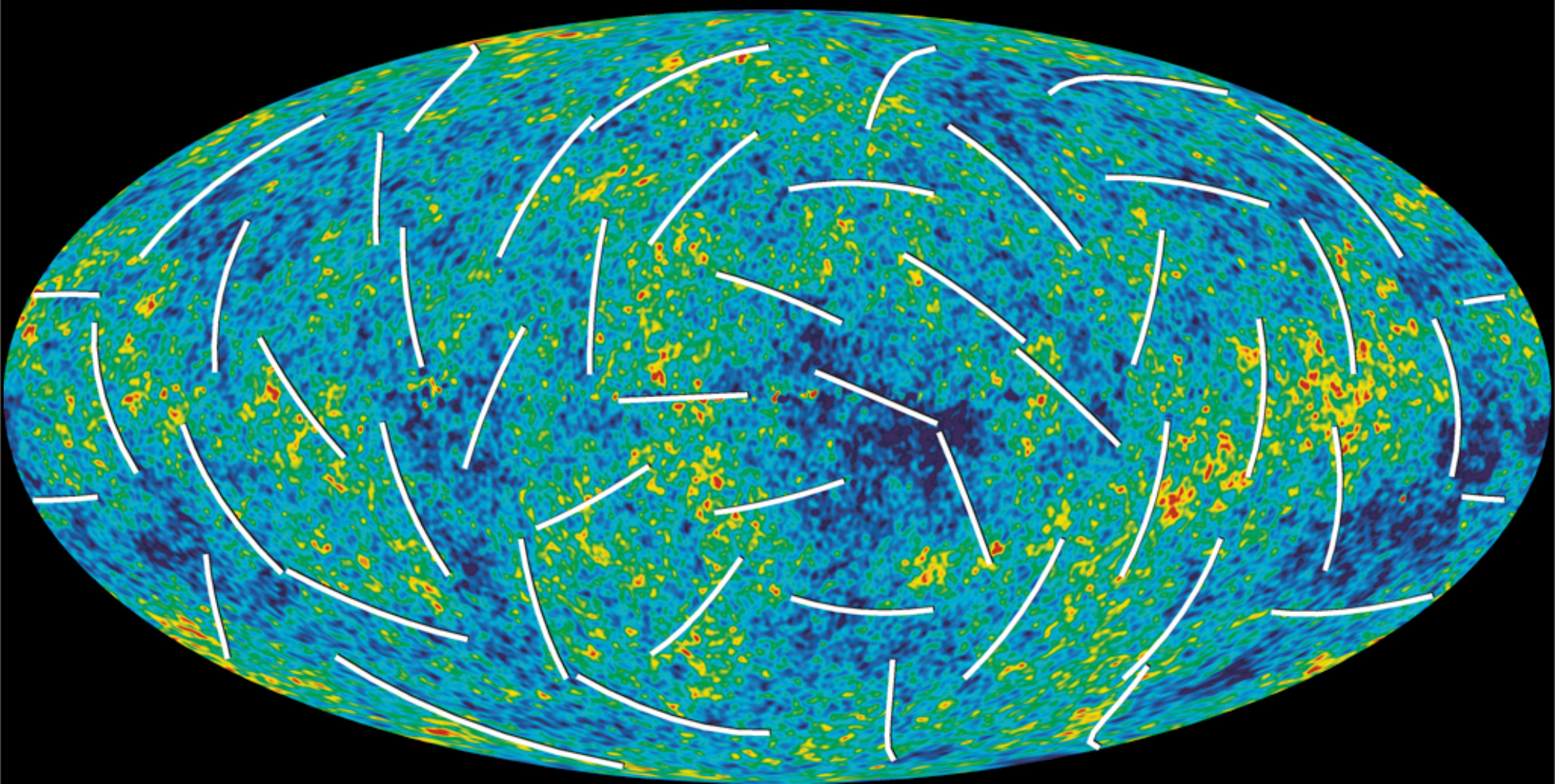
$l_{max}=2$

Significance

- Dipolar modulation ($l_{max}=1$), $\Delta(-2\ln L) = -3.4$ for 3 extra parameters
- Quadrupolar ($l_{max}=2$), $\Delta(-2\ln L) = -8.0$ for 8 extra parameters
- The low l C_l s are unaffected as are the multipole modes of T
- Note that we could easily boost the significance were we to choose *a posteriori* a direction, but no physical motivations so far
- We conclude that more evidences are required for such a radical reinterpretation of our data

Conclusions

- WMAP has now produced well characterized temperature and polarization maps
- After removing the galactic foregrounds, WMAP has detected EE and TE signatures of reionization with optical depth of 0.09
- Simple flat Λ CDM cosmological model has survived its most rigorous test and challenges fundamental physics
- Data favors red spectral index (with values consistent with simple inflationary models) over Harrison-Zeldovich Peebles spectrum
- The combination of WMAP data and other astronomical data now places even stronger constraints on the density of dark matter and dark energy, the properties of neutrinos, the properties of dark energy and the geometry of the Universe
- All the data and the derived products (time ordered data, maps, noise covariance matrices, likelihood codes, Markov chains) are all available on Lambda <http://lambda.gsfc.nasa.gov> . We are looking forward your analysis!



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